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Driving behavior analysis at work zones and rural intersections using SHRP 2 naturalistic driving data

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Driving behavior analysis at work zones and rural intersections using SHRP 2 naturalistic driving data

by

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ABSTRACT

Research studies have shown work zones and rural intersections vulnerable to numerous crashes. In 2015 alone, there were around 96,700 crashes in work zones, an approximate 7.8% increase from 2014. Out of all the crashes, around 0.7% of the crashes involved at least one fatality with statistics showing work zone crashes occurring once every 5.4 minutes during that year (Facts and Statistics – Work Zone Safety, 2017). In addition, rural intersection crashes account for around 30% of crashes in rural areas with more than 80% of rural intersections fatalities occurring at rural unsignalized intersections (Golembiewski and Chandler, 2011). Crashes in rural areas are often severe because of higher approach speeds and longer emergency response times (Gonzales et al 2009). Past studies have given more priority to assess the safety effectiveness of various countermeasures mostly in terms of crash analysis both in work zones and rural intersections. However, little is known on the driving behavior of vehicles at advance warning area of work zones and driving behavior of vehicles at nonstop controlled approaches of rural intersections.

This study utilized SHRP 2 Naturalistic Driving Study (NDS) data and Roadway Information Database (RID). Using both the data set, the study developed statistical models to analyze driving behavior upstream of work zones and rural intersections.

The first study developed a mixed effect logistic regression model to analyze the driving behavior in advance warning area of work zones to find the effectiveness of different work zone signs. The result showed first work zone sign was not significantly affecting the driving behavior. Only speed limit, lane ends and CMS were found to be affecting the driving behavior. Active CMS was found to be more effective compared to

not active CMS sign. Effect of overlapping signs was not found to have significant effect on the driving behavior. Speed limit with both work zone and feedback type were found to be significantly effective compared to normal speed limit signs with no indication of work zone. Speeding drivers were more likely to show response at different work zone signs with exception for drivers speeding at first sign. Distracted drivers were less likely to show response at work zone signs.

The second study built a mixed effect linear regression model to find different factors behind the response point of turning major street vehicles. The result showed that right turning vehicles started to show reaction to the turning maneuver slightly ahead to left turning vehicles. More than 70% of drivers showed reaction within 300 meters upstream of intersection for both types of turning maneuver. In addition, the study found driving speed at reaction point significantly affecting its location from intersection. Drivers speeding than the posted speed limit were associated with reaction point farther from the intersection.

In third study, a mixed effect logistic regression model was developed to find different factors affecting driving behavior of through moving vehicles at rural intersections. The result from this study showed that about 32% of drivers showed response to the intersections by decreasing speed by at least 3 miles per hour. Vehicles were more likely to show response to intersection at the time of presence of vehicles at the minor approaches. Non experienced drivers were found to be aware of the intersection ahead compared to experienced drivers. Drivers operating speed above 5 miles per hour were more likely to show response point. Intersections with intersection ahead warning signs was found to affect the response point positively.

CHAPTER 1. INTRODUCTION

1.1 Background

1.1.1 Work Zone Crashes

In 2015 alone, there were around 96,700 crashes in work zones area, 7.8% increase from 2014. This translates to around a work zone crash every 5.4 minutes. Around 0.7% of the crashes involved at least one fatality (Facts and Statistics – Work Zone Safety, 2017). Other research studies have also shown increase in the crash rate at work zone locations (Nemeth and Migletz 1991; Graham et al. 1977; Rouphail et al. 1988). Work zone crashes are also not only a problem for the traveling public, but they are a serious concern for highway workers. Each year from 2005 to 2010 more than 100 construction workers fatalities were reported with vehicle collision responsible for 14% of the above fatalities (Worker Safety, 2017).

Work zone crashes have been attributed to a number of factors such as work zone configuration, speeding, and driver characteristics. A study by Harb et al. 2008 found different contributing factors to work zone crashes as roadway geometry, age, gender, time of day, and influence of alcohol. Based on 2014 work zone crash database, speeding was found to be responsible for 28% of the fatal crashes with in work zone area (Facts and Statistics – Work Zone Safety, 2017). Speeding as a major contributing factor at work zone crashes have been supported by various research studies (Hallmark et al. 2015a, Garber and Zhao, 2002; Paulsen et al. 1978; Garber and Gadiraju, 1981; Garber and Woo, 1990). Other contributing factors behind work zone crashes are human error (Daniel et al. 2000), restricted lane width (Pigman, 1988), inefficient traffic control (Ha and Nemeth, 1995) and following too close (Hall and Lorenz, 1989).

Regarding the crash location at work zones, a study from Garber and Zhao, 2002 investigated the characteristics of work zones crashes in Virginia from 1996 to 1999. The number of police crash records were analyzed at different sections in work zones: advance warning, transition, buffer areas, activity and termination. The study found more number of crashes at the activity area compared to other area and might be due to difference in exposure time resulting from difference in length of each section. However, the study found rear-end collision as a dominant type of crash type and are even more dominant in the advance warning areas. In addition, Pigman, 1988, found higher severity index of crashes, which was defined as Equivalent Property-Damage-Only accidents by the total number of accidents, at advance warning zone compared to transition and work zone locations (2.46 to 1.94 and 2.28).

1.1.2 Rural Intersection Crashes

Rural intersections crashes account for around 30% of total crashes in rural area with more than 80% of rural intersection fatalities occurring at rural unsignalized intersections (Golembiewski and Chandler, 2011). Crashes in rural areas are often severe because of higher approach speed and longer emergency response times (Gonzalez et al. 2009). A study by Bauer and Harwood, 1996 found that on average 1.5 fatal and injury type crashes occurred at unsignalized intersections in rural area compared to average of 9.6 crashes at signalized intersections in urban areas. Due to large number of unsignalized intersections compared to signalized intersections at rural area, it clearly shows larger number of crashes at rural unsinalized compared to urban signalized intersections. The most predominant types of crashes at unsignalized intersections is angle crashes that typically occurs when vehicles from stop or yield controlled approach fail to give right of way to other approach vehicle.

Figure 1 below shows the distribution of different types of crashes at unsignalized intersections.

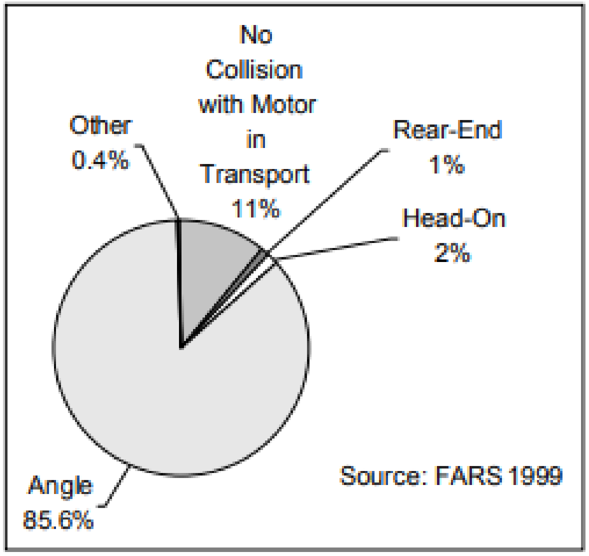

Figure 1 Manner of fatal crashes at unsignalized intersections (Neuman, 2003)

One of the major contributing crash factors at rural stop controlled intersections is inappropriate gap selection (Chovan et al. 1994; Preston et al. 2004). Another contributing factors is failure to yield which is influenced by driver age (McGwin and Brown, 2003; Keay et al. 2009), speeding, vision obstruction, and inattention/distraction (Campbell et al. 2004).

1.1.3 Background on Second Strategic Highway Research Program (SHRP 2)

1.1.3.1 SHRP 2 Naturalistic Driving Study

SHRP 2 Naturalistic Driving Study was conducted by Virginia Tech Transportation Institute (VTTI). The study collected 3092 driver's real world driving data from six different states (Florida, Indiana, New York, North Carolina, Pennsylvania and Washington). The study was conducted from October 2010 to November 2013 (Dingus et al. 2014). Driver's vehicles were equipped with data acquisition system (DAS) with forward and rear radar, four video cameras, lane tracking system, and data storage system which collected information like speed, acceleration, pedal position, GPS data, forward, rear, shoulder and face video. The driving data for each driver are available in a comma separated-values (csv) file. Figure 2 below showing placement of various units as a framework of data acquisition system for SHRP 2 project.

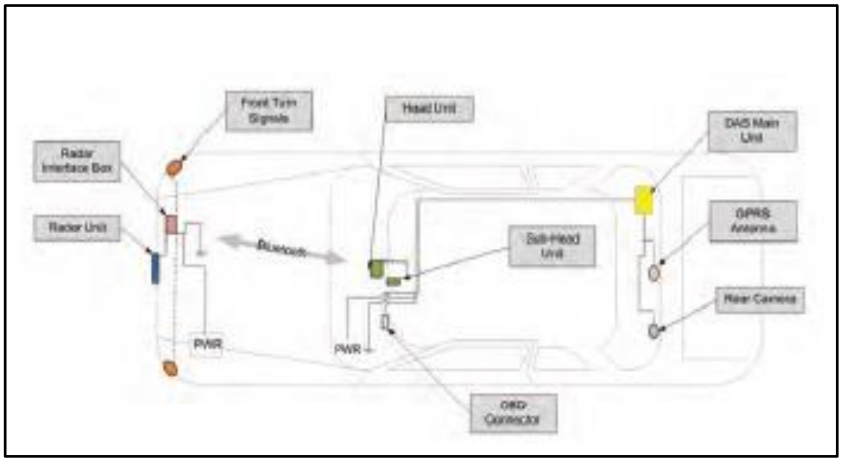

Figure 2 Framework of data acquisition system (Campbell, 2012)

1.1.3.2 SHRP 2 Roadway Information Database

A roadway information database (RID) was developed by Center for Transportation Research and Education (CTRE) at Iowa State University. A mobile data collection van was used to collect about 12,500 centerline miles in six different states where Naturalistic Driving Study sites. Data collected includes curve, barriers, intersections, highway lighting, medians, shoulders, rumble strips and different roadway signs. This allow researchers to use roadway information of the routes used in NDS trips. The driving data from NDS can be linked to the roadway database to get the roadway features. Roadway features collected includes Curve radius, number of lanes, roadway alignment, signing, intersection and types, lane width, grade, shoulder types, and lighting. The roadway data was collected using an instrumented mobile van driving at a posted speed limit (Smadi, 2015).

1.2 Literature Review

1.2.1 Change Point Methodology

A change point methodology was used in several of the analyses to indicate where a driver began reacting to a particular feature. Change point analyses have been used in various other fields to identify as the point that divides data into distinct homogenous segment (Eckley et al. 2011) or an abrupt or unexpected change in data with change in time series (Kawahara and Sugiyama, 2009; Sharma et al. 2016). Several methods are available to detect change point locations based on change in mean or variance (Haccou et al. 1998; Chen and Gupta, 1987; Fryzlewicz, 2014; Gerard-Merchant et al. 2008; Matteson and James, 2013) or change in parameters of the fitted linear segments (Muggeo, 2003). The selection of suitable methodology highly depends on the nature of the data used for the study. Its application is in varieties of fields: ecology (Beckage et al. 2007), economics (Talwar, 1983), climate science (Campra and Morales, 2016), medicine (Barros and Nunes, 2010; Yang et al. 2006; Malladi et al. 2013; Staudacher et al. 2005), and image analysis (Radke et al. 2005). As a limitation to note, change point models itself has many issues regarding the choice of segment boundaries, and the number of change point locations (Hawkins, 2001).

In summary, change point methodologies can be classified based on either detection of single or multiple change points. Research studies have used different approaches to detect change points. Few of the approaches widely used by various research studies are Piecewise regression, Bayesian Methods, Binary Segmentation, Circular Binary Segmentation, Wild Binary Segmentation, Segment Neighborhood Search, Pruned Exact Linear Time (PELT), CUSUM-based test, Likelihood-ratio, and Minimum description length. Selection of the suitable approach highly depends on the features of available data and the research questions. Table 1 below shows the list of few research studies that used different approaches for change point detection. As a note, circular and wild binary segmentation are an updated version of basic binary segmentation.

Table 1 Few research studies using different approaches for change point detection

Methodology	Research studies
Piecewise regression	Muggeo, 2003; Yu et al. 1999
Bayesian Methods	Kang, 2015; Xuan, 2007; Barry and Hartigan, 1993; Western and Kleykamp, 2004; Park and Dunson, 2010; Elliott and Shope, 2003
Binary Segmentation	Scott and Knott, 1974; Sen and Srivastava, 1975; Killick et al. 2012
Circular Binary Segmentation	Olshen et al. 2004
Wild Binary Segmentation	Fryzlewicz, 2014
Segment Neighborhood Search	Auger and Lawerence, 1989; Braun et al. 2000
Pruned Exact Linear Time(PELT)	Killick et al. 2012
CUSUM-based test	Zhang and Shao, 2010
Likelihood-ratio	Hinkley 1970; Chen and Gupta, 1997
Minimum description length	Davis et al. 2006

To test efficiency of the proposed methodology based on any of the above mentioned approaches, research studies have used different platforms. The most commonly used platform is simulation (Kim et al. 2004; Killick et al. 2012; Western and Kleykamp, 2004). Although different methodologies available in different statistical software, R was the chosen methodology. As a result, following sections only focus on the methodologies that are available in R.

Muggeo, 2008 used “segmented” package in R to fit linear model in each segment. The change in slope between two linear segments were tested to detect the presence of significant change. Erdman and Emerson, 2007 offered a new R implementation of the Bayesian change point procedure originally proposed by Barry and Hartigan, 1993. They developed a package “bcp” in R to conduct bayesian change point analysis. Killick and Eckley, 2014 developed a package in R called “changepoint” which contains Segment Neighborhood, Binary Segmentation and PELT methods available to detect change point locations. Types of penalty available in those functions are AIC, BIC, and SI. However, a user specific penalty term is required for change point detection. The package uses changes in mean, variance and both mean and variance in the data set to detect change point locations. A different approach was used by James and Matteson, 2015 in “ecp” package. The methodology is able to detect any type of distributional change within a data series. Unlike most of the packages in R, this package is able to perform multiple change point analysis for both univariate and multivariate time series. The package is able to determine the number of change points without user input. Bai and Perron, 2003 introduced “breakpoints” to detect break in the data series. A “strucchange” package is also available in R to detect change in the structure of the data set (Zeileis et al. 2002). Later, Ross, 2015 developed a “cpm” package in R, which provides a fast implementation of all the above change point models in both batch (Phase I) and sequential (Phase II) kind of data set. The sequence may contain either a single or multiple change points (CP). Both parametric and non-parametric test can be performed by using this package. Table 2 below shows the summary of above-mentioned packages in R with list of functions used for analysis with few additional details.

Table 2 Few software packages available in R

Method	**Function in R**	**Univariate**	**Multivariate**	**Single CP**	**Multiple CP**
Package “Segmented”	fit.lm or fit.glm	Yes	Yes	Yes	Yes
Package “changepoint”	cpt.mean cpt.variance cpt.meanvariance	Yes	No	Yes	Yes
Package “ecp”	e.divisive e.Agglo	Yes	Yes	Yes	Yes
Package “bcp”	Alternative package to “breakpoint”	Yes	No	Yes	Yes
Project “cpm”	Batch detection and Sequential detection	Yes: detectchangepoint	Yes: Processstream	Yes	Yes

Piecewise linear regression is widely used to detect changes in the data series. Karl et al. 2000 used autoregressive intervention moving average (ARMA) models in Monte Carlo experiments to fit piecewise trend to detect break points in global temperature. Similarly, Toms and Lesperance, 2003 defined piecewise linear regression approach as “broken-stick” models and used this approach to identify economical threshold. Each of the piecewise linear regression model was fit based on the weightage determined from inverted F test and examining profile log-likelihood contour. Grossi et al. 2001 proposed a statistical procedure to detect discontinuities or changes in multiscale landscape pattern. They used piecewise regression approach to fit linear models in each segment. Holmes and Mallick, 2001 used similar piecewise linear regression approach and used bayesian approach to fit linear models in each segment. Tome and Miranda, 2004 proposed new methodology based on piecewise regression approach to detect changes in overall trend of climate data. The new methodology used least square approach to fit best linear model in a given time series. Campra and Morales, 2016 used piecewise linear regression approach and fit linear model by using segmented package in R developed by Muggeo, 2003 to estimate multiple break points. An assumption of normality (Shapiro-Wilks and Anderson-Darling tests), independence (Ljung-Box test) and homoscedasticity (Breusch-Pagan test) were performed by performing test on residuals from piecewise regression. Similarly, Hallmark et al. 2015a used the same “segmented” package in R to identify reaction point of drivers to the start of work zone.

Based on the nature of data used for this study, piecewise linear regression approach was considered suitable to detect multiple change points along a speed profile with in the study area. This approach is simpler and results are easy to interpret. A “segmented” package in R is used to fit linear models in each segment. Significance test of detected change point was done using Davies test.

1.2.2 Driver Decelerating Behavior

Paolo and Sar, 2012 analyzed the speed of vehicles approaching to work zones in order to analyze drivers speed behavior. Data were collected from tangent sections of 11 work zones on two-lane rural roads with either physical reduction in the carriage width or not. Result showed deceleration rate was maximum near to the lane ends sign. No speed change was detected at temporary speed limit sign. Average deceleration rate varied between 0.32 to 0.81 m/s2. At final 20 meter to the work zone start, average deceleration rate was 1.70 m/s2 though very few drivers around 15% decelerated at the rate of 2 m/s2. Another study by Harwood et al. 1988 found 1.5 m/s2 of deceleration rate to slow down at uncontrolled intersections. The study also found an average deceleration rate of 0.68 m/s2 for the major-road vehicle over the entire distance traveled from its point of maximum speed to its point of minimum speed. Maurya and Bokare, 2012 summarized the list of papers associated with the deceleration rates at various roadway features and traffic control devices. The study found deceleration rate from 0.28 to 4.9 m/s2 at various roadway features and traffic control devices.

1.2.3 Driving Factors and Crashes

National Motor Vehicle Crash Causation Survey (NMVCCS) investigated an estimated 2,189,000 crashes nationwide during two and half year period from year 2005 to 2007 to check several factors behind crash occurrence (Singh, 2015). Several aspects of crash occurrence; pre-crash movement, critical pre-crash event, critical reason, and the associated factors were investigated in detail. The study defined critical reason as the immediate reason or contributing factors for the critical pre-crash event which is the last failure leading to the crash. The study assigned estimated 94% of critical reason to drivers and remaining were assigned to vehicles, environmental factors and unknown critical reason. The result showed how driving behavior affect likelihood of crashes. Another study by Dingus et al. 2014 used crash event data set from Naturalistic driving study to evaluate different crash casual factors. The data set used for this study consists of 905 injurious and property damage crash events. The result from this study showed driving related factors like error, impaired fatigue, and distraction were associated with 90% of crashes. The result also showed speeding increased the crash risk by around 13 times compared with the model driving (alter, attentive and sober driving).

1.2.4 Speed and Associated Crash Risk

Elvik et al. 2004 found that speed increases the risk of being involved in crashes. The result from this study showed that 10 percent reduction in mean speed of traffic will result in 37.8 percent reduction of the number of fatalities. A study conducted by Finch et al. 1994 found that every 1 mph increase in average speed increases the risk of accident by five percent. Many other studies have also found higher accident risk for fast travelling drivers (Kloeden et al. 2002; Taylor et al. 2000).

Aarts and Schagen, 2006 reviewed different empirical studies on speed and associated crash risk. Based on different research studies, the study found evidence of increase in the crash rate with an increase in speed on the minor roads than major roads. In addition, lane width, junction density, and traffic flow were also found to interact with the speed crash rate relationship. The study also found evidence that larger speed difference between vehicles are associated with higher crash risk. However, study did not find any conclusion regarding association of crash rate to slow moving vehicle.

Garber and Ehrhart, 2000 developed a model to study mathematical relationship between change in crash rate to change in speed, flow and geometric characteristics. The study was conducted within 52 locations in Virginia from 1993 to 1995. Speed data were collected from speed monitoring stations installed by Virginia Department of Transportation. Traffic volume, crash data and geometric characteristics of roadway were used to develop the model. Models were developed separately by roadway segments with different speed limits. Models developed at freeway segment with 65 mph and two lane non-freeways showed increase in the crash rate as standard deviation of speed increases.

Kloeden et al. 1997 analyzed the relation between traveling speed and risk of involvement in crash. By using case control study design, speed of cars involved in crashes were compared to speed of cars not involved in crashes in a roadway with speed limit of 60 kmph. The study found cars involved in crashes were travelling with higher than the speed limit. 68% of the cars involved in crashes were travelling with more than 60 kmph. No cars travelling below 60 kmph were associated with risk of involvement in crash.

1.2.5 Identification of Reaction Points

Hallmark et al. 2015a identified the reaction point to the work zone using "segmented" package available in R. The study found that drivers on average starts to show reaction at a distance of 140 feet from the start of work zone with some drivers showing reaction very close to the start of work zone (76.8 feet). However, the sample size used was very less. Oneyear et al. 2016 also used "segmented" package to identify braking behavior of both major and minor approach vehicles at stop controlled rural intersections.

1.3 Suitable Methodology for Change Point Detection

Change point methodology as discussed below was used for each trace to detect the locations of change point for the research questions mentioned in coming sections.

1.3.1 Description of Model

Change point model based on piecewise linear regression approach was used to detect change points to different work zone signs. All the detected points were available with p-value and confidence levels. Individual model was developed for each time series trace using speed as a dependent variable. As mentioned above, a change point model based on piecewise regression approach was used to detect change points. The response variable i.e. speed was split into two or more intervals in a predefined upstream section and a linear model is fitted in each interval. The length of section for each trace starts from minimum of 200 feet upstream of first work zone sign to the start of work zone. Depending on the placement of first sign, the length of upstream section differed by work zones. "Segmented" package in R was used to fit the linear regression model in each interval. The model used for this package is as follows: $y=\beta_{0}+ \beta_{1} D+ \beta_{2} (D-D^{*})$, where: Y is the dependent variable for each model; D is distance upstream from beginning of work zone or rural intersection (negative value); and D* is change point (the distance at which the driver reacts). Change points was detected if there is a significant difference in the slope of the fitted models (Muggeo, 2008). Davies test was used to check if detected change points are significant. Previous studies have already used this package to identify reaction point at work zones (Hallmark et al. 2015a) and horizontal curves (Hallmark et al. 2015b).

1.4 Legibility Distance

The general guidance for selecting the letter height is based on the legibility index of 30. It is the distance in feet at which a sign should be legible at 30 feet with one inch capital letters, or legible at 300 feet with ten-inch capital letters. MUTCD used the sign legibility distance of 180 feet for advance warning signs like signal ahead, intersection warning signs, stop ahead signs considering 6-inch letter height with the legibility index of 30. The other factor affecting the legibility distance are perception time, reaction time of drivers, time of a day, acuity of vision of drivers, and age of the drivers. Bertucci, 2006 mentioned that the minimum distance of the sign legibility depends on the time it takes to read the sign and the decisions and maneuvers required to comply with the sign. As the speed increases the rate of viewing distance decreases which means drivers need more distance to view the entire message at higher speed. In addition, legibility depends on the sign placement if it is perpendicular or parallel. Overall, legibility distance is a complex phenomenon where drivers should have suitable time to detect it, read and at the end react to the displayed message based on the surrounding traffic scenario. The distance differ by the types of work zone signs and the speed of the moving traffic.

A general guidance on displaying the message on Dynamic Message Sign (DMS) or Changeable Message Board (CMS) discussed that DMS used on roadways with speed limits of 55 mph or higher should be visible from half mile under both day and night conditions. The message should be designed to be legible from a minimum of 600 ft. for nighttime conditions and 800 ft. for normal daylight conditions (DMS). MUTCD also recommend changeable message signs should be legible from at least 600 feet for nighttime and 800 feet for daylight conditions (Changeable Message Signs).

A research study by Perez et al. 2016 showed that mean legibility distance for speed limit signs were close to 1,250 feet though the type and placement of speed limit signs was different. Signs were placed overhead rather than on the side of road. In addition, research showed double the legibility distance for symbols than that of the alphanumeric signs (Jacob et al. 1975).

Research studies have also found that increase in the letter height does not linearly or proportionally increase the legible distance. For instance, double the letter height does not double the legibility distance (Allen et al. 1967). Garvey and Mace, 1996 found that increases in letter height greater than about 8 inches resulted in non-proportional increases in the legibility distance. Usually, FHWA provides legibility distance based on the character height that is required for certain speed (Portable Changeable Message Sign Handbook).

The study by Paniati, 1988 used FHWA sign simulator to show a legibility distance equivalent to 90 meters (295 feet) for the lane merging sign (W4-1) (closest to lane drop sign that they included in the test). Another study by Zwahlen et al. 1991 did actual field tests and found legibility for W4-1 to be close to 900 feet which is significantly larger compared to that from the previous study.

Finally, based on findings from various research studies and using own engineering judgement this study used various distance as legibility distance for different types of work zone signs. For Static work zone signs: General guidance for selecting letter height is based on legibility index which is 30 per inch of letter height as a minimum ratio of 1 inch of letter height per 30 feet legibility distance. Thus assuming 6-inch letter height the legibility distance is 180ft. For DMS signs the legibility distances was chosen to be 600 ft. for nighttime conditions and 800 ft. for normal daylight conditions. For simplicity and being on the conservative side, both nighttime and daytime legibility distances were taken to be 600ft. For arrowhead CMS signs the legibility distance was chosen to be same as 600 ft. as CMS text message boards to be on the conservative side. For Speed limit and speed feedback signs, given that there are different kinds of work one speed limit signs, assuming the average letter height of speed limit letters to be 15 inches, the legibility distance was calculated as: 30*15= 450ft.

For Lane ends signs, since the calculated distance are so different to each other, to be on the conservative side, legibility to that of speed limit sign was used. Table 3 below shows the summary of the legibility distance used for different types of work zone signs in this study.

Table 3 Legibility distance for different work zone signs

Types of Work Zone Sign	**Legibility Distance , in feet (in meter)**
Static Work Zone Sign with 5” letter height	180 (54.86)
CMS Signs	600 (182.88)
Arrowhead VMS or CMS	600 (182.88)
Speed Limit Signs (Normal, Work Zone, Feedback)	450 (137.16)
Lane Ends	450 (137.16)

1.5 Problem Statement

The main objectives of this research was to use suitable change point methodology and provide the better understanding of driving behavior upstream of work zones (also called advance warning area) and rural unsignalized intersections instead of analyzing driving behavior within the actual region. The study analyzed the effect of different roadway characteristics, driving information, environmental characteristics and driver information on the driving behavior upstream of the above-mentioned zones.

Work zone safety has been considered always on the top priority by suitable agencies due its safety effect on both the road users and workers. Different factors like speeding, age of drivers, time of a day are found to be few major factors contributing to work zone crashes. Number of countermeasures have been placed upstream and inside the work zone area to get the driver’s attention and encourage safe work zone driving. However, limited information are available regarding the effectiveness of different countermeasures or work zone signs.

Very little is known on the driving behavior upstream of the work zones especially the response of each driver to different types of work zone signs.

Similarly, rural unsignalized intersections are also considered on the top priority by suitable agencies due the higher fatality rate. Research studies have already found several reasons like failed to yield or stop at the minor approaches, difficulty judging appropriate gap at the minor approaches, and emergency response time behind higher fatality rate resulting in angle crashes between two vehicles from major and minor approaches. Several countermeasures are installed at both the major and minor approaches to reduce the severity of crashes. The focus of most of the research studies is to analyze driving behavior of minor approach vehicles to check how the driving changes with different countermeasures and how different system installed help minor approach vehicles to judge safe gap on the major approaches. However, very few research studies have considered major approach vehicles to analyze their driving behavior.

This study will develop three different models. One to evaluate the safety upstream of work zones in advance warning area and remaining two from rural unsignalized intersections by analyzing driving behavior using suitable change point methodology. The three different research questions are outlined below.

1.5.1 Research Question 1: How do Drivers Drive Upstream of Work Zones at the Presence of Different Work Zone Signs?

The main objective of this study was to assess where drivers begin responding to the upcoming work zone signs to improve mobility and safety with in work zones. The impact was assessed by identifying response points along the time series or speed trace using a suitable change point methodology within a defined study section. Considering work zones sign as nodes or objects, response points were then overlapped with various work zone signs incorporating their legibility distance to identify response points associated with a particular sign. A mixed effect logistic regression model was developed to predict the likelihood of a response point within a particular sign. Other factors considered in the model were work zone characteristics, environmental characteristics, driver information and other factors like location of vehicle. Some of the information to be used for the model are:

I. Work Zone characteristics: Different work zone signs, Location of signs, Type of work zone, Length of upstream section.
II. Environmental characteristics: Time of a day, Weather, Pavement condition.
III. Driver information: Sex, age, distraction, vehicle type.
IV. Other factors: Speed, Location of vehicle.

1.5.2 Research Question 2: How Far Drivers Driving on the Major Approach Respond to their Turning Maneuver to the Minor Approaches?

This section used the same change point methodology as used in the previous research topic. The methodology was used to detect first reaction point of drivers either turning left or right from major approaches to the minor approaches at rural two way stop controlled intersections. Driver information, intersection characteristics, advanced warning signs, and other information like pavement conditions, time of data were summarized and a model to predict likelihood of a driver reaction distance at major approach at a rural intersection was modeled using linear mixed model. The following factors were considered in the analysis:

I. Intersection characteristics: Slope of the approach, Types of treatment, Presence of separate turning lanes, Intersection ahead warning signs, Location of intersection in curve, Skewness of the turning lane.

II. Environmental characteristics: Time of a day, Pavement condition, Weather condition.

III. Driving factors: Stopped for crossing traffic, speed at reaction point, types of turn.

IV. Driver information: Sex, age, years of driving, number of violations, number of crashes.

1.5.3 Research Question 3: How Through Moving Vehicles on the Major Approach Traverse Unsignalized Intersections?

Similarly, this section also used the same change point methodology as used in the previous research topics. The driving behavior was analyzed if drivers showed any response to the upcoming intersection by decreasing the speed. The response point was defined before the start of detecting it within a defined study section. The main objective of this study was to find different factors where drivers showed response to the upcoming intersection by decreasing the speed. Based on the information of drivers response to the intersection, a binary variable to show if drivers show response to the intersection or not was created as a dependent variable and various factors like intersection characteristics, environmental characteristics, driving factors and driver information were considered when developing a mixed effect logistic regression model. The detail of different factors is as follows:

I. Intersection characteristics: Type of intersection, Posted speed limit, Separate turning lanes.

II. Driving factor: Speed.

III. Environmental characteristics: Time of a day, Pavement condition, Weather condition.

IV. Driver information: Sex, age, years of driving, number of violations, number of crashes.

1.6 Study Limitations

The study is also not without limitations. The brake activation variable was available in the time series file but due to some missing values in some traces, it was not always possible to use it as a variable of interest to detect reaction or change point. The study used speed as a variable of interest, the study threw few numbers of traces out from the study due to many missing cells in the speed column and only traces with high speed accuracy were used for the analysis. Only traces with availability of more than 90% of the speed data were used for the study.

Data was smoothed for few traces due to the presence of noise in the data set. Out of many smoothing functions in R, lowess function in R was used to smooth few traces. The smoother spline in the function can be changed to fit the structure of the raw data set so that major structure of the data remains the same. Traces with excessive noise were removed from the analysis. As only traces moving in a free flow conditions were used, the significant number of available traces were removed which limits the sample size for few variables of interest.

1.7 Scope

A common change methodology was used to assess the driving behavior at upstream of work zones and rural intersections to understand how drivers reacts to different roadway features, and signs. Three different models were developed: one at upstream or work zones and two at upstream of rural intersections by using speed as a metric to measure driving behavior. First, the model was developed to evaluate effectiveness of different work zone signs upstream of the work zone provides insight to different signs significantly affecting the driving behavior in terms of speed. The findings could be used by suitable agencies to better control speed of traffic approaching intersections by placing right work zone signs at the right location. It provides information on how variable upstream distance and number of work zone signs affect the driving behavior. The findings from this study can be used by suitable agencies to decrease traffic crashes and fatalities both inside and upstream of the work zones.

Second, the model developed from the rural intersections will help suitable agencies locating different warning sign ahead of the intersection both for turning vehicles and through moving vehicles at rural unsignalized intersections. Using result from this study, different speed control measures can be applied to reduce the approach speed which affect the severity at the time of angle collision. The model developed from major approach turning vehicles provides insight on how drivers shows response to the approaching intersections. It could help suitable agencies to prevent run off crashes at the time of turn and avoid collision with minor approach vehicles due to speeding with shorter reaction distance.

At the end, the model developed from the last section i.e. model developed from through moving major approach vehicle shows different factors affecting driver's response to the approaching intersection. This study can also help to know the effect of major approach vehicles on gap analysis of minor street vehicles.

1.8 Organization of the Dissertation

The dissertation consisted of five different chapters. Chapter 1 included background on work zone and rural intersection crashes followed by relevant previous literature on change point methodology, work zones and rural intersections. The detail description of the change point methodology used for this study was then described in detail to show how the methodology work. This section also included short description on the legibility distance. The section at the end provided detail discussion in the research objectives of the study followed by short description on study limitation and scope of the overall study.

Chapter 2 discussed the research question 1. It developed a model to find different significant work zone sign in addition to other relevant factors affecting driving behavior upstream of work zones. A change point methodology as discussed in section 1.3 was used to detect response point of drivers while passing by different work zone sings. Chapter 3 used the same change point methodology used in the previous chapter to address rural intersection by analyzing driving behavior of major approach turning vehicles upstream of rural intersections. This section developed a model to predict likelihood of reaction distance upstream. Chapter 4 discussed rural intersection safety by analyzing driving behavior of major approach through moving vehicles. The same changed point methodology used in previous two sections was used for the detection of response point.

Chapter 5 included conclusion based on the outcome from three research questions and the major contribution of the dissertation in terms of work zone and rural intersection safety. Further, it discussed limitations of the study along with additional research studies that can be conducted using the similar concept to address additional safety concerns. All the remaining items that were not of the primary interest were included in the Appendix.

1.9 References

2009 Edition Chapter 2L. Changeable Message Signs. Manual on Uniform Traffic Control Devices, 2009. U.S. Department of Transportation. Federal Highway Administration. https://mutcd.fhwa.dot.gov/htm/2009r1r2/part2/part2l.htm.

Aarts, L., and I. Van Schagen. Driving Speed and the Risk of Road Crashes: A Review. Accident Analysis & Prevention, Vol. 38, No. 2, 2006, pp. 215–224.

Allen, T. M., F. N. Dyer, G. M. Smith, and M. H. Janson. “Luminance Requirements for Illuminated Signs.” Highway Research Record 179, 1967, 16–37.

Atkinson, J. E., B. E. Chandler, V. Betkey, K. Weiss, K. Dixon, A. Giragosian, K. Donoughe, and C. O’Donnell. Manual for Selecting Safety Improvements on High Risk Rural Roads. Federal Highway Administration, Office of Safety, Washington DC, 2014.

Auger, I.E., and C. E. Lawerence. Algorithms for the optimal identification of segment neighborhoods. Bull. Math. Biol. 51, 39–54. 1989.

Bai J., Perron P. (2003), Computation and Analysis of Multiple Structural Change Models, Journal of Applied Econometrics, 18, 1-22.

Barros, P. P., and L.C. Nunes. The impact of pharmaceutical policy measures: An endogenous structural-break approach. Social Science & Medicine, 71(3), pp. 440-450. 2010.

Barry, D., and J. A. Hartigan. A Bayesian analysis for change point problems. Journal of the American Statistical Association, 88(421):309–319, 1993.

Bauer, K.M., and D.W. Harwood, "Statistical Models of At-Grade Intersection Accidents," Report No. FHWA-RD-96-125, Federal Highway Administration, McLean, VA, 1996.

Beckage, B., L. Joseph, P. Belisle, D.B. Wolfson, and W.J. Platt. Bayesian change-point analyses in ecology. The New Phytologist, 174(2), pp. 456-467. 2007.

Bertucci, A., Sign legibility rules of thumb. United States Sign Council. 2006 United States Sign Council. Accessed from:
http://www.usscfoundation.org/USSCSignLegiRulesThumb.pdf

Braun, J. V., R. K. Braun, and H.G. Muller. Multiple changepoint fitting via quasi likelihood, with application to DNA sequence segmentation. Biometrika, 87:301–314. 2000.

Campbell, B.N., J.D. Smith, and W.G. Najim. Analysis of Fatal Crashes Due to Signal and Stop Sign Violations. National Highway Traffic Safety Administration, US Department of Transportation. DOT HS 809 779. Sept. 2004.

Campbell, K. L. The SHRP2 Naturalistic Driving Study. Transportation Research News 282, October, 2012.

Campra, P. and M. Morales. Trend analysis by a piecewise linear regression model applied to surface air temperatures in Southeastern Spain (1973–2014), Non lin. Processes Geophys. Discuss., https://doi.org/10.5194/npg-2016-29, 2016.

Chen, J., and A. K. Gupta. Testing and locating variance changepoints with application to stock prices. Journal of the American Statistical Association, 92:739 – 747. 1997.

Chovan, J.D., L. Tijerian, J. H. Everson, J. A. Pierowicz, D. L. Hendricks. Examination of intersection left turn across path crashes and IVHS countermeasures (DOT HS 808 154). National Highway Traffic Safety Administration. 1994.

Daniel, J., K. Dixon, and D. Jared. "Analysis of fatal crashes in Georgia work zones." Transp. Res. Rec., 1715, 18–23. 2000.

Davis, R. A., T. C. M. Lee, and G. A. Rodriguez-Yam. Structural break estimation for nonstationary time series models. Journal of the American Statistical Association, 101(473):223–239. 2006.

Dingus, T. A., J. M. Hankey, J. F. Antin, S. E. Lee, L. Eichelberger, K. Stulce, D. McGraw, M. Perez, and L. Stowe. Naturalistic Driving Study: Technical Coordination and Quality Control. Virginia Tech Transportation Institute. Blacksburg, VA. 2014.

Dynamic Message Signs (DMS). Extracted from http://epg.modot.mo.gov/index.php?title=910.3_Dynamic_Message_Signs_(DMS)#910.3.2.5_Legibility_and_Visibility_of_DMS_.28MUTCD_2L.03.29

Eckley I. A, P. Fearnhead, and R. Killick "Analysis of Changepoint Models In book: Bayesian Time Series Models, Chapter: 10, Publisher: Cambridge University Press. 2011.

Elliott, M. and J. Shope. Use of a Bayesian changepoint model to estimate effects of a graduated driver's licensing program. Journal of Data Science, 1, 43-63. 2003.

Elvik, R., P. Christensen, and A. Amundsen. Speed and road accidents. An evaluation of the Power Model. TØI report 740/2004. Institute of Transport Economics TOI, Oslo.2004.

Erdman, C., and J.W. Emerson. bcp: An R Package for Performing a Bayesian Analysis of Change Point Problems. Journal of Statistical Software. 2007, Volume 23, Issue 3.

Facts and Statistics – Work Zone Safety. Work Zone Management Program. U.S. Department of Transportation, Federal Highway Administration. Last modified: July 10, 2017. Accessed on October 24, 2017. https://ops.fhwa.dot.gov/wz/resources/facts_stats/safety.htm.

Finch, D. J., P. Kompfner, C.R. Lockwood, and G. Maycock. Speed, speed limits and crashes. Project Record S211G/RB/Project Report PR 58. Transport Research Laboratory TRL, Crowthorne, Berkshire, 1994.

Fryzlewicz, P. Wild binary segmentation for multiple change-point detection. Ann. Statist. 42, 2243-2281. 2014.

Garber, N. J., and M. Zhao. "Crash characteristics at work zones." Rep. No. VTRC 02–R12, Virginia Transportation Research Council, Charlottesville, VA. 2002.

Garber, N. J., and R. Gadiraju. Speed Variance and Its Influence on Accidents. AAA Foundation for Traffic Safety, Washington, D.C. 1981.

Garber, N. J., and T. H. Woo. Accident Characteristics at Construction and Maintenance Zones in Urban Areas. VTRC 90-R12. Virginia Transportation Research Council, Charlottesville. 1990.

Garber, N., and A. Ehrhart. The Effect of Speed, Flow, and Geometric Characteristics on Crash Rates for different types of Virginia Highways. Virginia Transportation Research Council. Virginia Department of Transportation and the University of Virginia, Final Report, VTRC 00-R15.2000.

Garvey, P. M., and D. M. Mace. Changeable Message Sign Visibility. Publication No. FHWA-RD94-077, 1996.

Gerard-Merchant, P. G. F, D. E. Stooksbury, and L. Seymour. Methods for starting the detection of undocumented Multiple Changepoints. Journal of Climate 21:4887–4899. 2008.

Golembiewski, G.A., and B. Chandler. Intersection Safety: A Manual for Local Rural Road Owners. Federal Highway Administration, Washington, DC, FHWA-SA-11-08, 2011.

Gonzalez, R. P., G. R. Cummings, H. A. Phelan, M. S. Mulekar, and C. B. Rodning. Does Increased Emergency Medical Services Prehospital Time Affect Patient Mortality in Rural Motor Vehicle Crashes? A Statewide Analysis. The American Journal of Surgery, Vol. 197, 2009, pp. 30-34.

Graham, J.L., R.J. Paulsen, and J.C. Glennon. Accident and Speed Studies in Construction Zones. Report No. FHWARD-77-80, Federal Highway Administration, Washington D.C., June 1977.

Grossi, L., G. Zurlini, and O. Rossi. Statistical detection of multiscale landscape patterns. Environmental and Ecological Statistics 8, 253-267, 2001.

Ha, T., and Z.A. Nemeth. "Detailed study of accident experience in construction and maintenance zones." Transp. Res. Rec., 1509, 38–45. 1995.

Haccou, P., E. Meelis, and S. Geer. The likelihood ratio test for the change point problem for exponentially distributed random variables. Stochastic Processes and Their Applications, 27:121–139. 1988.

Hall, J. W., and V. M. Lorenz. Characteristics of Construction Zone Accidents. In Transportation Research Record 1230, TRB, National Research Council, Washington, D.C., 1989.

Hallmark, S, O. Smadi, and A. Sharma. Evaluation of Work Zone Safety Using the SHRP 2 Naturalistic Driving Study Data. Phase I Final Report and Phase II Proposal. SHRP 2 Implementation Assistance Program. Center for Transportation Research and Education at Iowa State University's Institute for Transportation, September 2015a.

Hallmark, S.L., N. Oneyear, S. Tyner, and B. Wang. Analysis of Naturalistic Driving Study Data: Roadway Departures on Rural Two-Lane Curves. SHRP 2, Transportation Research Board. Washington D. C., 2015b.

Harb, R., E. Radwan, X. Yan, A. Pande, and M. Abdel-Aty. "Freeway work-zone crash analysis and risk identification using multiple and conditional logistic regression." J. Transp. Eng., 1345, 203–214. 2008.

Hawkins, D. M. Fitting multiple change-point models to data. Computational Statistics & Data Analysis, 37, 323–341.2011.

Hinkley, D. V. Inference about the change-point in a sequence of random variables. Biometrika, 57:1–17. 1970.

Holmes, C., and B. Mallick. Bayesian Regression with Multivariate Linear Splines. Journal of the Royal Statistical Society. Series B (Statistical Methodology), 2001, 63(1), 3-17.

James, N.A, and D. S. Matteson. "ecp: An R Package for Nonparametric Multiple Change Point Analysis of Multivariate Data," Journal of Statistical Software, Volume 62, No. 7: 1-25. 2015.

Kang, S. "Bayesian change-point analysis in linear regression model with scale mixtures of normal distributions", Master's Thesis, Michigan Technological University, 2015. http://digitalcommons.mtu.edu/etds/920.

Karl, T. R,, R. W. Knight, and B. Baker. The record breaking global temperatures of 1997 and 1998: Evidence for an increase in the rate of global warming? Geophys. Res. Lett.27, 5,719-722, 2000.

Kawahara, Y and M. Sugiyama, “Sequential Change-Point Detection Based on Direct Density-Ratio Estimation,” in SIAM International Conference on Data Mining, 2009, pp. 389–400.

Keay, L., S. Jasti, B. Munoz, K.A. Turano, C.A. Munro, D.D. Duncan, K.Baldwin, D.J. Baneen-Roche, E.W. Gower, and S.K. West. Urban and rural differences in Older drivers Failure to Stop at Stop Signs. Accident Analysis and Prevention. Vol. 41, Issue 5. September 2009. pp. 995-1000.

Killick R, and I. A. Eckley. changepoint: An R Package for Changepoint Analysis. Journal of Statistical Software. Volume 58, Issue 3. 2014. DOI: 10.18637/jss.v058.i03.

Killick, R., P. Fearnhead, and I.A. Eckley, I. A. Optimal detection of changepoints with a linear computational cost. JASA, 107(500):1590 – 1598. 2012.

Kim, H. J., M.P, Fay, B. Yu, M.J. Barrett, and E.J. Feuer. "Comparability of segmented line regression models." Biometrics 60(4): 1005-1014. December 2004.

Kloeden, C. N., A. J. McLean, and G. Glonek. Reanalysis of travelling speed and the rate of crash involvement in Adelaide South Australia. Report No. CR 207. Australian Transport Safety Bureau ATSB, Civic Square, ACT. 2002.

Kloeden, C. N., A. J. McLean, V. M. Moore, and G. Ponte. Travelling Speed and the risk off Crash Involvement. NHMRC Road Accident Research Unit, The University of Adelaide. November 1997.

Malladi, R., G. P. Kalamangalam, and B. Aazhang, “Online Bayesian change point detection algorithms for segmentation of epileptic activity,” in Asilomar Conference on Signals, Systems and Computers, 2013, pp. 1833–1837.

Manual on Uniform Traffic Control Devices (MUTCD). (https://mutcd.fhwa.dot.gov/).

Matteson D. S., N. A. James. A nonparametric approach for multiple change point analysis of multivariate data. J Am Stat Assoc. 109(505):334–345. doi:10.1080/01621459.2013.849605. 2013.

Maurya, A.K., and P. S. Bokare. Study of Deceleration Behaviour of Different Vehicle Types. International Journal for Traffic and Transport Engineering, 2012, 2(3): 253 – 270.

McGwin, G. and D.B. Brown. Characteristics of Traffic Crashes Among Young, Middle-aged, and older Drivers. Accident Analysis and Prevention. Vol. 31, Issue 3. May 1999. pp. 181-198.

Muggeo, V.M.R. Estimating regression models with unknown break-points. Statistics in Medicine 22, 3055–3071. 2003.

Muggeo, V.M.R. R Package to Fit Regression Models with Broken-Line Relationships. R News, Vol. 8, No. 1, 2008, pp. 20–25.

Nemeth, Z.A., and D.J. Migletz. Accident Characteristics Before, During, and After Safety Upgrading Projects on Ohio's Rural Interstate System. Transportation Research Record 672. Transportation Research Board, National Research Council, Washington D.C., 1978, pp. 19-24.

Neuman, T. R., R. Pfefer, K. L. Slack, K. K. Hardy, D.W. Harwood, I. B. Potts, D. J. Torbic, E. R. K. Rabbani. Guidance for Implementation of the AASHTO Strategic Highway Safety Plan Volume 5: A Guide for Addressing Unsignalized Intersection Collisions. NCHRP Report 500. Project G17-18(3) FY'00, 2003. Transportation Research Board Washington, D.C. 2003.

Olshen, A. B., E. S. Venkatraman, R. Lucito, and M. Wigler, M. "Circular binary segmentation for the analysis of array-based DNA copy number data." Biostatistics 5(4): 557-572. 2004.

Oneyear, N., S. Hallmark, and B. Wang. Evaluating the Relationship between the Driver and Roadway to Address Rural Intersection Safety using the SHRP 2 Naturalistic Driving Study Data. 2016. Iowa Department of Transportation and Federal Highway Administration (InTrans Project 13-476).

Paniati, J. F. Legibility and comprehension of traffic sign symbols. In Proceedings of the Human Factors Society Annual Meeting (Vol. 32, No. 10, pp. 568-572), 1988, October, Sage CA: Los Angeles, CA: SAGE Publications.

Paolo, P. and D. Sar. "Driving Speed Behaviour Approaching Road Work Zones on Two-Lane Rural Roads." Procedia - Social and Behavioral Sciences 53: 672-681. 2012.

Park, J., and D. Dunson. BAYESIAN GENERALIZED PRODUCT PARTITION MODEL. Statistica Sinica, 20(3), 1203-1226. 2010. Retrieved from http://www.jstor.org/stable/24309487.

Paulsen, R. J., J. C. Glennon, and J. L. Graham. Traffic Safety in Construction Zones. Rural and Urban Roads, Vol. 16, No. 10-71. 1978.

Perez, W.A., M. A. Bertola, and B. Philips. Active Traffic Management: Comprehension, Legibility, Distance, and Motorist Behavior in Response to Selected Variable Speed Limit and Lane Control Signing. Federal Highway Administration. Report No. FHWA-HRT-16-037, June 2016. https://www.fhwa.dot.gov/publications/research/safety/16037/16037.pdf.

Pigman, J. G., R. A. Kenneth. Analysis of accidents in construction and maintenance work zones. Frankfort: Kentucky Transportation Research Program, 1988. Report Number UKTRP-88-13. Report Date 6-1988.

Portable Changeable Message Sign Handbook – PCMS. USDOT Federal Highway Administration, 2003. Publication Number: FHWA-RD-03-066..

Preston H, R. Storm, M. Donath, and C. Shankwitz. Review of Minnesota's Rural Intersection Crashes: Methodology for Identifying Intersections for Intersection Decision Support. Minnesota Department of Transportation. St. Paul, MN. MN/RC-2004-31. 2004.

Radke, R.J., S. Andra, O. Al-Kofahi, and B. Roysam, "Image change detection algorithms: a systematic survey," IEEE Trans. Image Process., vol. 14, no. 3, pp. 294–307, Mar. 2005.

Rouphail, N.M., Z.S. Yang, and J. Fazio. Comparative Study of Short- and Long-Term Urban Freeway Work Zones. Transportation Research Record 1163. Transportation Research Board, National Research Council, Washington D.C., 1988, pp. 4-14.

Scott, A. J. and M. Knott. A cluster analysis method for grouping means in the analysis of variance. Biometrics, 30(3):507–512. 1974.

Sen, A., and M. S. Srivastava. On tests for detecting change in mean. The Annals of Statistics, 3(1):98–108. 1975.

Sharma, S., D. A. Swayne and C. Obimbo. 2016. Trend analysis and change point techniques: a survey. Energ. Ecol. Environ. 1(3):123–130DOI 10.1007/s40974-016-0011-1. 2016.

Singh, S. Critical reasons for crashes investigated in the National Motor Vehicle Crash Causation Survey. (Traffic Safety Facts Crash Stats. Report No. DOT HS 812 115). Washington, DC: National Highway Traffic Safety Administration. 2015.

Smadi, O. SHRP2 Roadway Information Database. Institute for Transportation. Ames, IA, 2015.

Staudacher, M., S. Telser, A. Amann, H. Hinterhuber, and M. Ritsch-Marte, "A new method for change-point detection developed for on-line analysis of the heart beat variability during sleep," Phys. A Stat. Mech. its Appl., vol. 349, no. 3–4, pp. 582–596, Apr. 2005.

Talwar, P. P. Detecting a shift in location: Some robust tests. Journal of Econometrics, 23(3), pp. 353-367. 1983.

Taylor, M., D. A. Lynam, and A. Baruya. The effect of drivers' speed on the frequency of accidents. TRL Report TRL421. Transport Research Laboratory, Crowthorne. 2000.

Tome, A.R., and P. M. A. Miranda. Piecewise linear fitting and trend changing points of climate parameters. Geophysical Research Letters. Volume31, Issue2, January, 2004.

Toms, J. D., and M. L. Lesperance. Piecewise regression: a tool for identifying ecological thresholds. Ecology 84(8):2034-2041. DOI:10.1890/02-0472., 2003.

Western, B., and M. Kleykamp. A Bayesian Change Point Model for Historical Time Series Analysis. Political Analysis, 12(4), 354-374. 2004. Retrieved from http://www.jstor.org/stable/25791783.

Worker Safety. Work Zone Management Program. U.S. Department of Transportation, Federal Highway Administration. Accessed on October 24, 2017. https://ops.fhwa.dot.gov/wz/workersafety/index.htm.

Xuan, X. Bayesian Inference on Change Point Problems (Master of Thesis). The University Of British Columbia. 2007. Retrieved from: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.186.6055&rep=rep1&type=pdf.

Yang, P., G. Dumont, and J. M. Ansermino, “Adaptive change detection in heart rate trend monitoring in anesthetized children.,” IEEE Trans. Biomed. Eng., vol. 53, no. 11, pp. 2211–9, Nov. 2006.

Yu, J-R, G-H. Tzeng, and H-L. Li. A general piecewise necessity regression analysis based on linear programming. Fuzzy Sets and Systems 105 (1999) 429–436.

Zeileis, A., F. Leisch, K. Hornik, and C. Kleiber . strucchange: An R Package for Testing for Structural Change in Linear Regression Models. Journal of Statistical Software, 7(2), 1–38. 2002.

Zhang, X, and X, Shao. Testing for Change Points in Time Series. Journal of the American Statistical Association, September 2010, Vol. 105, No. 491, Theory and Methods. DOI:10.1198/jasa.2010.tm10103. © 2010American Statistical Association.

Zwahlen, H. T., X. Hu, M. Sunkara, and L. M. Duffus. "Recognition of traffic sign symbols in the field during daytime and nighttime." In Proceedings of the Human Factors Society Annual Meeting, vol. 35, no. 15, pp. 1058-1062. Sage CA: Los Angeles, CA: SAGE Publications, 1991.

CHAPTER 2. ASSESSING DRIVING BEHAVIOR UPSTREAM OF WORK ZONES BY DETECTING RESPONSE POINTS IN SPEED PROFILE: A NATURALISTIC DRIVING STUDY

Revised from a paper to be submitted in Transportation Research Part F: Traffic Psychology and Behavior

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Abstract

Work zones are vulnerable to numerous crashes both within moving traffic and workers. Various research studies have analyzed driving behavior upstream and inside the work zone. However, little is known on the detail effect of different work zone signs upstream on the driving behavior. Using 299 speed traces from 4 lane roadway with both shoulder and lane closure scenario, the study analyzed driving behavior within the advance warning area from the first sign to the start of work zone. Response points were detected along each speed trace with in the study section where drivers reduced speed by ≥ 3mph. Assuming work zone signs location as nodes a mixed effect logistic model was developed.

The summary of response points by different work zone signs showed that drivers were more likely to response near to the first sign and static work zone signs compared to changeable message sign (CMS) and speed limit signs.

The result from the model showed that first work zone sign was not significantly affecting the driving behavior. Only speed limit, lane ends and CMS were found to be affecting the driving behavior. Active CMS was found to be more effective compared to not active CMS sign. Effect of overlapping signs was not found to have significant effect on the

driving behavior. Except at speed limit signs, drivers were more likely to show response to the signs placed near to the work zones. Speed limit with both work zone and feedback type were found to be significantly effective compared to normal speed limit signs with no indication of work zone. Speeding drivers were more likely to show response at different work zone signs with exception for drivers speeding at first sign. Distracted drivers were less likely to show response at work zone signs. In addition, driver information and other environmental factors were not found to be significant in the model.

The findings from this study suggest effect of different work zone signs in advance warning area in the driving speed behavior to improve safety and mobility within that region.

Keywords: Work Zone Signs, Response Point, Speed, Advance Warning Area, Legibility Distance

2.1 Introduction

In 2015 alone, there were around 96,700 crashes in work zones, an approximate 7.8% increase from 2014. This translates to around a work zone crash every 5.4 minutes (Facts and Statistics – Work Zone Safety, 2017). Around 0.7% of the crashes involved at least one fatality. Work zone crashes are also not only a problem for the traveling public, but they are also a serious concern for highway workers. Each year from 2005 to 2010 more than 100 construction workers fatalities were reported with vehicle collision responsible for 14% of the above fatalities (Worker Safety, 2017).

2.1.1 Factors Affecting Work Zone Crashes

Work zone crashes have been attributed to a number of factors such as work zone configuration, speeding, and driver characteristics. A study by Harb et al. 2008 found different contributing factors to work zone crashes as roadway geometry, age, gender, time of a day and influence of alcohol. Based on 2014 work zone crash database, speeding was found to be responsible for 28% of the fatal crashes with in work zone area (Facts and Statistics – Work Zone Safety, 2017). Speeding as a major contributing for work zone crashes have been supported by various research studies (Hallmark et al. 2015a; Garber and Zhao, 2002; Paulsen et al. 1978; Garber and Gadiraju, 1981; Garber and Woo, 1990). Other contributing factors behind work zone crashes are human error (Daniel et al. 2000), restricted lane width (Pigman, 1988), inefficient traffic control (Ha and Nemeth, 1995); and following too close (Hall and Lorenz, 1989).

Crashes can occur in any area of the work zone but the advance warning and transition areas are particularly problematic since drivers are confronted with multiple competing pieces of information which may require action (i.e. need to slow, merge, pay attention to workers). This is exacerbated by driver distraction and speeding. Pigman, 1988 developed a severity index of crashes for work zone crashes which was defined as Equivalent Property-Damage-Only (EPDO) accidents divided by the total number of crashes. They found a higher proportion of severity index crashes in the advance warning zone compared to the transition area, and or activity area (2.46 to 1.94 and 2.28). Another study by Garber and Zhao, 2002 investigated the characteristics of work zones crashes in Virginia from 1996 to 1999. The study analyzed the number of police crash records at different sections in work zones: advance warning, transition, buffer areas, activity and termination. The study found more crashes at the activity area compared to other locations. However they did not account for section length which may skew results towards the activity area since they tend to be significantly longer than the advance warning or transition areas.

2.1.2 Driver's Speed Reduction at Work Zone Signs

The objective of the advance warning area is to alert drivers to the upcoming work area ideally resulting in attentiveness and when needed, a reduction in speed. Agencies have utilized a variety of countermeasures to get drivers attention and most studies to assess countermeasures have utilized reduction in speed as a surrogate safety measure. The reduction in speed due to presence of various countermeasures is shown below in detail.

2.2.2.1 Advance warning

Benekohal et al. 1992 evaluated the speed of vehicles at different locations in a construction zone at Interstate 57, near Mattoon, Illinois with the work zone configuration of one lane closed in each direction on a two lane per direction highway. Speed data were collected using the video images of total of 151 free flow vehicles travelling through the study section during a weekdays. The speed data at various influence points within the construction zone which included construction signs or roadway features were determined. Based on the speed profile, drivers were categorized into four different categories (Category 1: noticeably reduced speed at the first speed limit sign, Category 2: Travelled faster than the speed limit and did not significantly reduced speed, Category 3: ignored both the speed limit and construction activities, Category 4: Other than 1, 2 and 3) while drivers showing speed change of less than 5 mph was not used in the criteria. The study evaluated the change in speed at many influence points within the work space. The result showed 63% of drivers reduced speed after passing first work zone speed limit sign (Category 1), only 11% reduced speed at near to the location of construction activities (category 2) and 11% did not reduce their speed limit at all (category 3). Drivers were found to decrease the speed limit to the lowest level near to the work space.

Finley et al. 2014 observed speed of the traffic both at upstream and inside the work zones. All of the work zones used for the study had speed limit of 10 mph below the original posted speed limit with different work zone configurations like lane shift, lane closure, and temporary diversion. Speed data were analyzed at different nodes. Speed characteristics at upstream of work zone showed that 85th percentile speed was greater than the posted speed limit with 85th percentile speed within 5 mph in 82% of the sites and between 6 to 7 mph over the original posted speed limit. Variation in the speed upstream was found to be between 11.3 and 33.8 mph. They also found that 85th percentile speeds at the first work zone speed limit sign with a work zone condition visible were still 3 to 11 mph over the reduced speed limit. They also indicate that motorist only reduce their speed limit if they clearly perceive a need to do so.

2.2.2.2. Variable Message Signs

Thompson, 2002 studied the effect of trailer mounted changeable message sign as shown in Figure 3. The study found change in the mean speed during the activation-on compared with the time of activation-off of variable or changeable message sign. Mean speed was reduced from 55 mph to 48 mph when the changeable message sign was on. Hanscom, 1982 found that changeable message sign that provided warning of an upcoming lane closure reduced speeds by up to 7 mph. Dixon and Wang, 2002 found reduced speed near sign by 6-7 mph immediately adjacent to the change message sign with radar in upstream of work zone but its effect did not extent to work zone area. Brewer et al. 2006 found 2 mph reduction in 85th percentile speed downstream of the location of portable changeable message sign. The study found orange-border speed limit signs to be less effective than changeable message sign in reducing 85th percentile speed. In addition, a study by Sorel et al. 2006 found reduction in mean speed of 3 to 10 mph due to changeable message signs. Wang et al. 2003 studied the effect of changeable message sign in addition to fluorescent orange sheeting and innovative message signs with radar. The signs were used for reducing speeds in work zones. Data were collected both from upstream and inside the work zone. Result showed changeable message sign with radar significantly reduced the vehicles speed on the vicinity of sign by 8 mph. On the other hand, fluorescent orange sheeting and innovative message signs were able to reduce speed by 1 to 3 mph and 0.2 to 1.8 mph respectively.

Figure 3 Trailer mounted changeable message sign (Thompson, 2002)

2.2.2.3 Speed Feedback Sign

Brewer et al. 2006 evaluated the level of driver compliance on three different work zone signs: speed display trailers, changeable message signs and orange bordered speed limit signs. Result showed device that display the speed of vehicles has the most significant effect in reducing the speed compared to static speed limit signs. Similarly, McCoy et al. 1995 evaluated the effectiveness of speed monitoring display (as shown in Figure 4) installed at work zone on an interstate highway in South Dakota. Mean speed of vehicles were found to reduce by 4 to 5 mph. The sign was also able to reduce the percentage of vehicles exceeding the advisory speed limit from 20 to 40%.

Maze, 2000 also evaluated the effect of speed monitor display. Though the result showed decreased in the mean and 85th percentile speed, the decrease was not statistical significant. Meyer, 2003 evaluated an effect of radar actuated speed display. The evaluation was done on a two lane rural commuter routes on the west of Lawrence, Kansas and data were collected for about 8 weeks. Before and after data were compared to see an effect of speed displays on speed. Both mean and 85th percentile speed were significantly decreased by about 5 miles per hour. Percentage of drivers speeding above 5 mph dropped from 30% to less than 5%. Richards et al. 1985 found that a Changeable Message Sign (CMS) showing a speed limit message reduced vehicles speed by an average of 3 mph. Both "Speed-Only Message" and "Speed and Information Message" reduced the mean speed in the range of 0 to 5 mph. Carlson et al. 2000 studied upstream and work zone area separately to find the effectiveness of speed display trailers. Nine work zones: four with two lane highways with flagger operations and remaining five with multi-lane highway with single lane closed located in rural high speed temporary work zones were used for the study. LIDAR guns and piezoelectric sensors were used to track the speed of vehicles approaching to work zones. In work zones with lane closure operations, vehicles were found to reduce significantly higher at speed display trailers between 2 to 7.5 miles per hour upstream of work zone and 3 to 6 miles with in the work zone. Other research studies have also shown reduced mean speed by 2 to 7 miles per hour due to speed display trailer (Saito et al. 2003; Carlson et al. 2000; Meyer, 2000; Hall and Wrage, 1997; Jackels and Brannan, 1988; Richards et al. 1985).

Figure 4 Speed monitoring display (McCoy et al. 1995)

2.2.2.4 Variable speed limit

Kwon et al. 2007 found variable speed limit sign was effective reducing longitudinal speed difference in work zones during weekday morning peak hours. A study by Edara et al. 2013 observed an average speed reduction of 2.2 mph on a roadway of 50 mph speed limit with and without Variable Advisory Speed limit Sign in an uncongested traffic flow. However, Lyles et al. 2004 found mixed result regarding the effect of variable speed limit signs and concluded that the system may be able to reduce speed for vehicles at higher speeds. Riffkin et al. 2008 studied the effect of system at the night time and found decrease in sped of 1 to 5 mph. Figure 5 below shows the trailer mounted variable speed limit sign.

Figure 5 Variable speed limit sign (Edara et al. 2013)

2.2.2.5 Speed Limit Only

A study by Finley, 2008 found, in general, the 85th percentile speed downstream of a reduced work zone speed limit sign decreased slightly (on average by 3 mph) though the operating speed was still 9 to 16 mph over the work zone speed limit. In 2014, Finley et al. 2014 compared digital speed limit signs with static speed limit signs in work zone areas. The study found decrease in 85th percentile speed limit due to digital speed limit sign from 1.0 to 12.1 mph at different sites. Similarly, 85th percentile speed limit due to static speed limit sign decreased from no change to 13 mph at different sites. Richards et al. 1985 found that a CMS showing a speed limit message reduced vehicle speeds by an average of 3 mph. Brewer et al. 2006 compared orange-border speed limit sign with the changeable message signs. The result showed that orange-border speed limit sign was found to be less effective than changeable message sign in reducing 85th percentile speed.

2.2.2.6 Enforcement Signs

Benekohal et al. 1992 found that police patrolling by circulating in the 4 miles sections of work zone activity in work zone with 2 lanes in each direction with one lane closed in each direction, an average speed of cars and trucks in the work zone were reduced by about 4 to 5 mph. In 2010, Benekohal et al. 2010 studied the effect of Speed Photo-radar Enforcement (SPE). The system reduced an average speed of free-flowing cars by 6.3-7.9 mph traveling on median lane and 4.1-7.7 mph traveling on shoulder lane. Due to SPE, free flowing trucks reduced speed in the median lane by 3.4-6.9 mph and in the shoulder lane by 4.0-6.1 mph. SPE was found to be more effective with the presence of police car. Finley et al. 2014 found that in the vicinity of law enforcement 85th percentile speed limit decreased by 14 miles per hours at all the sites. However, researchers also found the difference between stationary and circulating patrol car. Richards et al. 1985 found that stationary patrol car was able to reduce mean speed by 4-12 mph and circulating patrol car was able to reduce mean speed by 2-3 mph. In a different paper, Richards et al. 1985 also found a speed decrease of 9 to 15 mph due to stationary patrol car.

2.1.3 Objectives

Although work zones only make up a fraction of the driving environment, they account for around 2 percent of roadway fatalities annually and account for 14% of worker fatalities. Driver behavior in the advance warning area is particularly of interest since drivers are confronted with multiple competing pieces of information which may require action (i.e. need to slow, merge, pay attention to workers). This is exacerbated by driver distraction and speeding.

The main objective of this study was to assess where drivers begin reacting to the upcoming work zone and the impact of various work zone signs or traffic control. Change in speed of a certain threshold was used to identify response points upstream of each work zone using a change point methodology. Response points were then correlated to individual work zone signs and the impact of different sign types on driver response was assessed using a logistic regression model. Other factors such as work zone characteristics, environmental characteristics, driver information and other factors like location of vehicle were also considered in the model.

2.1.4 Data

The study utilized data from the SHRP 2 NDS data and Roadway Information Database (RID). The SHRP 2 NDS is the largest and most comprehensive NDS undertaken to date with over 3,000 volunteer passenger vehicle drivers, ages 16–98 from sites in six US states: Florida, Indiana, New York, North Carolina, Pennsylvania, and Washington. Data, such as speed, acceleration, braking, and lateral position, were collected in-vehicle using a data acquisition system (DAS) and collated to 0.1 second intervals (time series). Video views of the forward roadway, rear roadway, driver face, and over the driver’s shoulder were also collected. Global Positioning System (GPS) data are included as data variables and allow spatial matching with roadway features. The SHRP NDS are stored at a secure data enclave at the Virginia Tech Transportation Institute (VTTI). Detailed roadway characteristics were collected in tandem for about 12,000 centerline miles within the study sites. The Roadway Information Database (RID) also secured data from existing data sources such as state DOTs and the Highway Performance Monitoring System. This included roadway characteristics, traffic volume, 511, and other supplemental data which covered most roadways for the study site in each state.

Primarily, the 511 data served as the main source of data for finding out construction and maintenance events for this study. The 511 system is a resource for national travelers and it is set up and run by the United States DOT and FHWA. Currently 35 states participate in the 511 system. The system allows drivers to dial “511" on their phones and receive real-time traffic information on road closures, accidents, route detours, weather alerts, etc. These data were archived and included in the RID.

The RID supplemental data that contains 511 information was queried for each of the three years the NDS was active (2011 to 2013). The resulting data included around two million records. The 511 files contained information about any traffic event occurring within the study state, including construction. Potential work zones were identified using an attribute query in ArcGIS with key words such as “construction,” “lane closure,” “road work,” or “maintenance” were used. Some information about the duration of the event was usually available, and potential work zones in place for more than three days were identified. Three days was used as a threshold because it was unlikely that a sufficient number of NDS time series traces would be available for short-duration work zones. Ultimately, 9,290 potential work zones were identified.

The next step linked the identified 511 events to the RID data. Locations for the 9,290 potential work zones were sent to VTTI, and the number of time series traces and drivers' age/gender information for the links of interest were requested. Potential work zone trips were determined by identifying the trips falling within the dates indicated in the 511 data. Work zones with at least fifteen potential trips were selected. In order to request time series traces, it was necessary to make some estimate of the physical extent of each potential work zone. Dynamic segmentation was used to add links upstream and downstream of each identified work zone. When 511 data were presented as a point, dynamic segmentation was used to extract links two miles upstream and downstream of the point. A buffer was also created around each potential work zone to increase the likelihood that the actual work zone was included.

Forward videos associated with time series traces were requested for each work zone. The forward video was reviewed to determine whether a work zone was actually present. The beginning and end points of each work zone, initially identified, were adjusted based on a review of the forward video and corresponding spatial location from the time series data. Once again dynamic segmentation method was used to find “link IDS”, one mile upstream and downstream of each work zone.

The final and the most reliable step towards finding work zones of interest was manually reviewing NDS forward videos. A large amount of useful information was manually coded from the forward view video that identified the active work zones with different configurations. This was necessary since no machine visioning tools were available and development of such tools was beyond the scope of this project.

NDS data were provided from VTTI and include time series traces which is one trip by one driver through a particular work zone. A time series trace was provided for each event in the form of a CVS file with information including a time stamp (data were provided at 0.1 second intervals), position, speed, forward acceleration, lateral acceleration, wiper position status, brake status, lane position variables, etc. A video clip showing the forward roadway and a video clip showing a rear roadway view were also provided. A video clip of the driver face and hand position was accessible at the VTTI secure data enclave and was utilized to reduce driver characteristics.

This study focused on active work zones for 4-lane divided roadways. Active work zones included those were a lane or shoulder closure were present. Only traces with good speed data (less than 10% missing speed data) within the advance warning area were used. Additionally only traces which could be considered as “freeflow” were utilized. The advance warning area distance was different for each work zone since traffic control configurations vary. As noted above, the advance warning area extended 200 feet upstream of the first work zone sign to the beginning of the first taper. 200 feet was provided based on the legibility distance to the first sign. This resulted in 299 time series traces corresponding to 142 unique drivers and 25 unique work zones on 4 lanes divided roadway with either lane or shoulder closures as shown in Table 4.

Table 4 Summary of traces used in the response model

Type of Work Zone	**Total number of traces**	**Unique Drivers**	**Unique Work Zones**	**States**
All	299	142	25	(PA = 140 and NY = 159)
Shoulder Closed	82	56	8	
Lane Closed	217	107	19	

All signs included in the work zone influence area were included in the analyses. Location of signs were identified in relation to the time series trace. As a result, a vehicle position in relation to each work zone feature was available at 0.1 second intervals. Figure 6 shows the average location of work zone signs in relation to the beginning of taper for the shoulder closure or lane closure. SL shows the average location of all speed limit signs while SL-Normal, SL-Work Zone and SL-Feedback shows the average location of speed limit signs by types. As noted, CMS signs, when present, were typically placed near the first work zone sign. Other descriptive statistics associated with the signs like minimum, maximum and standard deviation is shown below in the data summary table in detail.

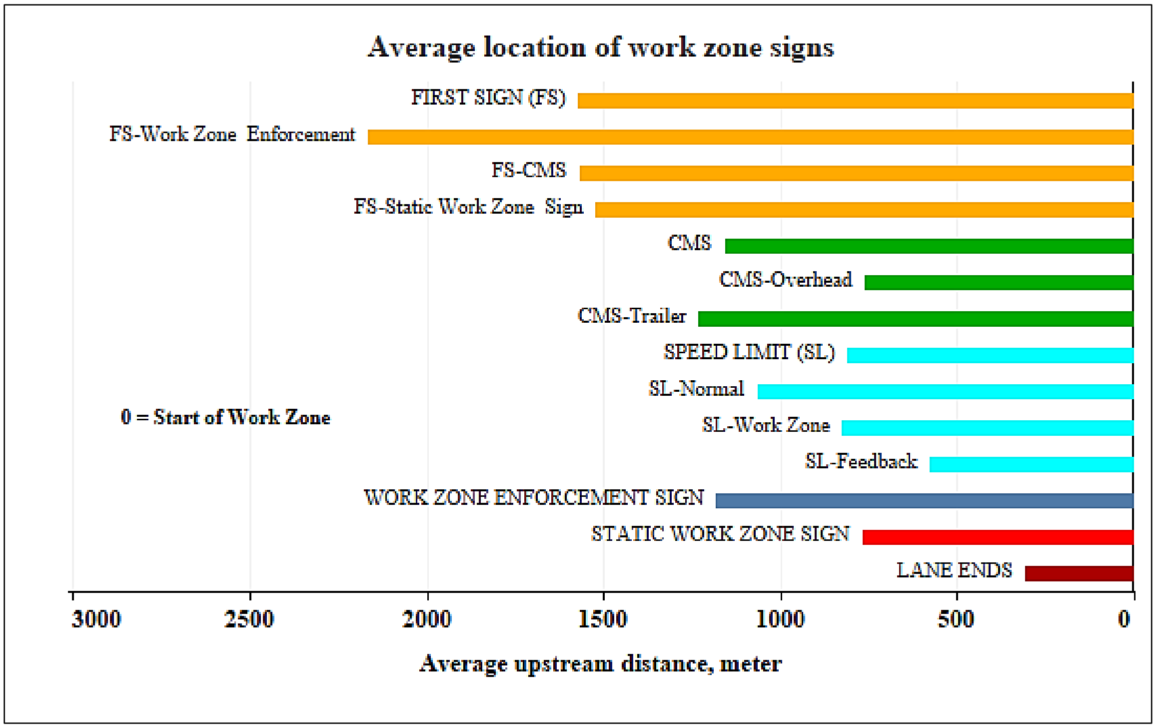


Figure 6 Average distance of of work zone signs in relation to start of work zone

A change point model was developed for each of the 299 time series traces that included the advance warning area. Statistically significant change or response points were detected for each trace using the speed and acceleration threshold described in the previous section. As shown in Figure 7, around 15% of the speed traces (46) had no discernable response points for any work zone feature. As shown, the majority of drivers had one or two response points in the advance warning area while 6% had 3 or more response points. This suggest most drivers reacted only a couple of times as they approached the work zone.

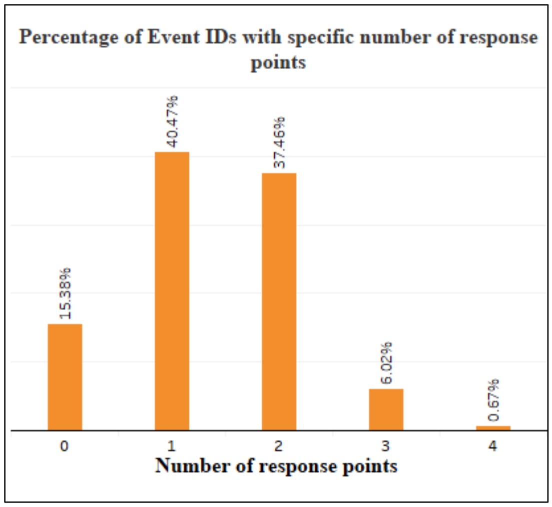


Figure 7 Percentage of speed traces (Event IDs) with associated number of response points

2.2 Methodology

2.2.1 Analysis Area

The study evaluated driver response upstream of the work zone in order to determine what work zone characteristics that got a driver's attention. Among different components of temporary traffic control zones defined in Manual on Uniform Traffic Control Devices (MUTCD), the advance warning area was used for this study. The upstream section ends at the start of first taper which marks the transition area then extends upstream to a point 200 feet before the first work zone sign. The 200 feet distance is to account for drivers being able to see the first sign in advance of the actual sign location and was based on legibility distance. In this study, the first work zone sign is the first sign in advance work zone area that indicates the upcoming presence of a work zone.

2.2.2 Data Reduction

Roadway characteristics such as number of lanes, regular speed limit, and roadway geometry were queried from the RID. Work zone characteristics such as direction of travel, lane or shoulder closures, types and location of work zone signs, vehicle lane position, start of work zone, and presence of vehicle ahead (if any) were manually extracted from the forward video. Time of day and roadway surface condition (wet versus dry) were also coded from the forward video.

Work zone characteristics were reduced from the beginning of the advance warning area to a few meters downstream of the transition area. A data reduction template and data dictionary was prepared at the beginning to maintain consistency among many data reducers. Categories of work zone signs reduced included the following:

I. Static Work Zone Signs: It included all normal work zone warning signs such as “Road Work Ahead” or “Begin Work Zone”.

II. Changeable Message Signs (CMS): It refer to the digital message signs placed on the side or overhead of the road showing information relevant to work zone ahead. It was further coded as either “trailer” mounted on the side of the road or “over” mounted on the top of the road. Depending on if it was flashing information or not, it was reduced either active or not active.

III. Speed Limit: It refer to the regular posted speed limit signs, work zone specific speed limit signs, or speed feedback signs. Normal speed limit signs were existing regulatory speed limit signs. For the upstream section, they served as the regulatory speed limit unless a work zone speed limit superseded the normal speed limit. Work zone speed limit signs were reduced as work zone type when they were placed additionally specific to work zone and usually provided in orange color background. The remaining type, feedback, displayed flashing numbers either showing the posted speed limit or individual vehicle speed with posted speed limit on the top.

IV. Enforcement Signs: It included signs which provided information about penalties for driver actions in the work zone such as “Work Zone: Traffic Fines Double”

V. Lane Ends: It indicated a lane merge was ahead for work zones where a lane was closed.

VI. First Sign: It was the first work zone related sign that a driver was presented with as they entered the work zone advance warning area. It is the first sign that indicates work zone ahead. Any type of work zone sign can be the first sign. In this study, enforcement, static work zone signs and CMS were used as First Sign and was coded accordingly.

VII. Overlapping Effect: Whenever multiple signs were legible from a section, it was considered due to effect of multiple signs and was termed as overlapping effect.

VIII. In addition to location and type of signs, presence of vehicles ahead, lane merge locations, presence and location of equipment and workers, and weather information were also reduced.

2.2.3 Change Point Methodology

Change point models were used to detect response points for each time series trace within the work zone advance warning area. Surrogates such as speed (Paolo and Sar, 2012; Hallmark et al. 2015b), lane position (Reyes et al. 2008), acceleration and brake reaction distance (You et al. 2016) have been utilized by past research studies to assess whether drivers are aware of an upcoming change in the roadway environment.

Several methods are available to detect change point locations based on change in mean or variance or change in parameters of the fitted linear segments (Fryzlewicz, 2014; Gerard-Merchant et al. 2008; Matteson and James, 2013; Muggeo, 2003). Based on the nature of the data set, a piecewise linear regression approach was used to detect change points. Models were developed in R using "Segmented" package. A linear model was developed for each time series using speed as a dependent variable. Data were modeled for a distance of 200 feet upstream of the first work zone sign to the start of the work zone. Depending on the placement of first sign, the length of the upstream section differed by work zone. The model used for this package is as follows: $Y = \beta 0 + \beta 1\ D + \beta 3\ (D\text{-}D^*)$ where, Y is the dependent variable for each model, D is distance upstream from beginning of work zone (negative value); and D* is change point (the distance at which the driver shows response).

The model detects points if there is a significant difference in the slope of the fitted model (Muggeo, 2008). A Davies test was used to check if detected change points were significant. Thresholds can be set so that only changes of a certain magnitude are found. This is important since there is a certain amount of noise in the data and not all significant changes in speed necessarily indicate a driver is reacting.

2.2.4 Speed as a Surrogate for Driver Response

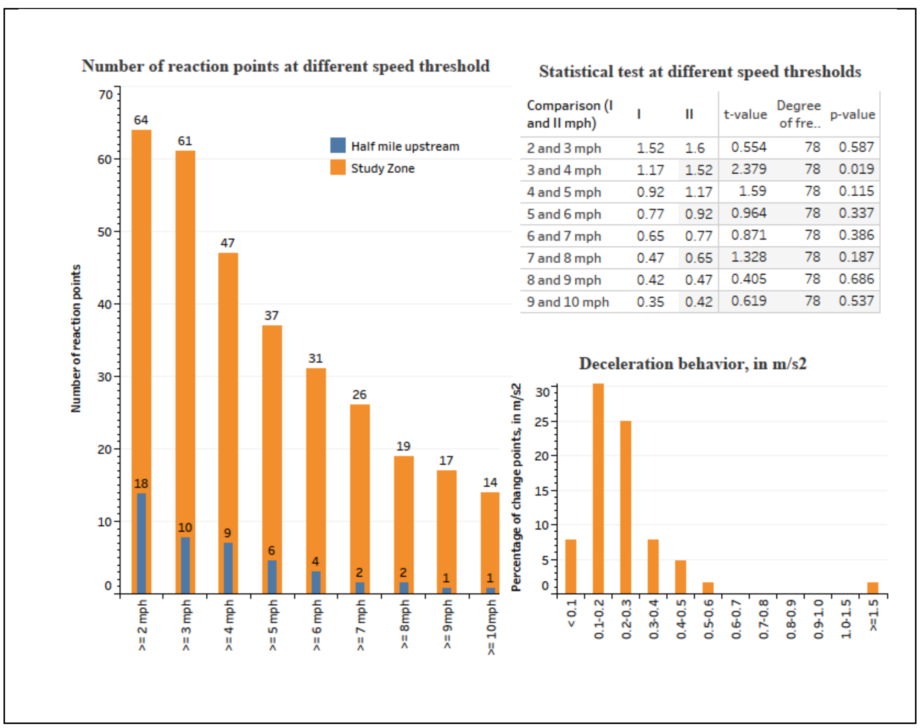
Different surrogates like change in acceleration (Chen et al. 2015), speed (Af Wåhlberg, 2008) and lane position (Sayer et al. 2007), pedal position pattern (Miyajima et al. 2006) and both acceleration and speed (Zeeman and Booysen, 2013) are used by different studies to detect abnormal or change in driving behavior. Steering wheel position has been used as a measure of driver attentiveness (Kircher and Ajlstrom, 2016; Bach et al. 2008). Several surrogate measures were considered based on what other researchers had utilized.

For the SHRP2 data set, steering wheel position could only be extracted from the OBD for a subset of vehicles due to differences in vehicle systems. As a result, it could not be utilized. Lane position is not accurate in a work zone since it relies on lane lines which are often obscured, missing, or overlapping. Pedal position was not available for a large number of traces and as a result would have resulted in a much smaller sample size. Forward acceleration was also considered but the manner in which acceleration was gathered resulted in a significant amount of noise. As a result identifying change points using acceleration would have been much more complicated than using speed. Additionally acceleration and speed are highly correlated. Since the speed data had less noise, was more likely to be reported at regularly in the data, and was a common measure used in the literature, speed was selected as the variable of interest to detect changes in driving behavior.

A change in speed was used as a surrogate for driver reaction or response. It was assumed that when drivers encounter a work zone feature, such as traffic control or equipment, they will decrease speed. However, in some cases drivers did not decrease speed when they encountered a work zone feature. They may have already slowed to a safe speed for work zone conditions and as a result there was no need for further action. Drivers may not change speed even when conditions indicate they should. Additionally a driver may see a work zone feature and become more alert and prepared to take action when needed but not slow down. However driver state cannot be detected, as a result, only reactions that manifested in a physical change could be identified.

2.2.5 Effect of Using Different Speed Threshold

Since numerous minor changes in speed were present in the time series traces, a threshold for what was indicative of a change in driver behavior was established. Various studies were consulted and it was found that many researchers used a speed reduction of 3 to 7 mph as a threshold to detect response to work zone signs (Sorel et al. 2006; Edara et al. 2013; Finley, 2008; Meyer, 2003; Benekohal et al. 2010; Finley et al. 2014). However, the scientific rationale for this range of thresholds was not explained in the available research. As a result, the team also considered the number of response point that would be identified at different thresholds using a range of 1 to 10 mph a set of sample speed traces. This was done to assess whether there was an obvious point at which the number of response points dropped off rapidly thus indicating a threshold between regular driving and actual speed reductions due to external stimuli. For instance, using a threshold of 1 mph would lead to a significant number of points since this is within the threshold of normal driving. Figure 8 below shows the distribution of number of response points with reduction in the speed with a range from 1 to 10 miles per hour both within the advance warning area and half mile upstream of it. It shows that large number of points with a threshold of ≥ 2miles per hour both in advance warning area and upstream of it shows reduction in speed as a part of the normal driving in the absence of external stimuli. Again, it shows number of response points dropped off rapidly after ≥ 3 miles per hour both with in advance warning area and upstream of it which indicates the effect of external stimuli. Thus the study assumed all the response points with speed reduction of < 3 mph as a part of the normal driving or noise in the data set.



Comparison (I and II mph)	I	II	t-value	Degree of fre..	p-value
2 and 3 mph	1.52	1.6	0.554	78	0.587
3 and 4 mph	1.17	1.52	2.379	78	0.019
4 and 5 mph	0.92	1.17	1.59	78	0.115
5 and 6 mph	0.77	0.92	0.964	78	0.337
6 and 7 mph	0.65	0.77	0.871	78	0.386
7 and 8 mph	0.47	0.65	1.328	78	0.187
8 and 9 mph	0.42	0.47	0.405	78	0.686
9 and 10 mph	0.35	0.42	0.619	78	0.537

Figure 8 Sample analysis showing number of response points at different speed thresholds within and upstream of study section

After careful evaluation of the sample speed traces, it was decided to use a threshold of ≥ 3 miles per hour (1.341 meter per second). The speed change threshold was also coupled with a deceleration rate of a certain magnitude. Otherwise, reduction in speed over a long distance would have been included. It was determined from sample speed traces that around 90% of response points were in the range of 0.1 to 1.5 m/s2 (meter per second square). Based on studies on driver deceleration behavior, the normal deceleration was discussed from 1.7 to 4.9 m/s2. These values represent the upper range of normal driving and could be used to filter out abnormal events, there was no information available to select a lower bound. A final threshold of ≥ 3 miles per hour with in a deceleration rate in the range of 0.1 to 2.0 m/s2 (0.2g) was considered as a threshold for further analysis. Based on the threshold, a response point was defined as a point with a reduction in speed of ≥ 3 mph with a deceleration rate of 0.1 to 2.0 m/s2. Only detected response points satisfying the criteria were used for the analysis.

Additionally, response points were reviewed in conjunction with the forward video and response points due to scenario such as a lane merge, traffic entering from ramp, and sudden braking due to traffic ahead were removed. The effect of roadway geometry (horizontal curve or grade) were was not considered since the grade was reasonably flat in most cases and no sharp horizontal were present.

2.3 Analysis and Results

2.3.1 Summary of Response Points by Signs

The locations of response points were overlain with the work zone sign locations to determine where response points occurred in relation to work zone features. The typical signs considered were Static Work Zone Signs, Changeable Message Signs, Speed Limit, and Lane Ends. Enforcement Signs and the scenario where multiple signs were overlapped within the buffer distance were excluded due to limited sample size (few response points within the buffer distance). The buffer distance was considered as 200 meter upstream and 80 meter downstream of each sign. Buffer distance was selected so that upstream 200 meter cover the legibility distances for all the signs. The downstream 80 meters cover the farthest response points located after the signs with estimation done based on the driver's normal reaction time of 2.5 seconds and average speed from the traces. This is a robust measure to estimate the average location of response points for each sign type. Response points were also summarized at 4 and 5 miles per hour threshold but no significant change was found (detail in Table C 18). Table 5 below shows the average location of response points for each type of signs.

For the First Sign, it shows that out of total response points detected within the buffer distance, 38.47% of drivers showed response after and remaining 61.53% showed response before the sign with an average of 30.41 and 56.44 meter respectively. Overall, it shows that drivers were more likely to respond closer to the First Sign and Static Work Zone Signs. However, drivers responded earlier to Changeable Message Sign and Speed Limit signs. It might be due to the difference in the legibility distance of a particular sign.

Table 5 Average location of response points with in the buffer distance of each sign

Signs	**Location**	**Proportion of response points, %**	**Average Distance of response point, in meter**	**Standard Deviation**
First Sign	Before	61.53	56.44	54.93
	After	38.47	30.41	21.09
CMS	Before	86.84	113.91	52.81
	After	13.16	33.78	30.53
Speed Limit	Before	78.37	85.31	49.35
	After	21.63	23.96	17.13
Static Work Zone	Before	67.61	57.04	49.86
	After	32.39	31.91	21.25
Lane Ends	Before	58.33	70.15	42.41
	After	41.67	32.80	17.14

2.4 Development of the Response Model

To develop the model, a buffer distance as developed in the previous section was set to the legibility distance of each sign to precisely assess the effect of signs. The legibility distance of each sign was determined and represented the likely distance where a driver was able to see the sign and therefore react to the sign. Based on MUTCD requirements and the information about sign legibility from the literature review, legibility distance were selected for each sign type as shown in the following Table 6.

Table 6 Legibility distance for different work zone signs

Types of Work Zone Sign	Legibility Distance , in feet (in meter)
Static Work Zone Sign with 5” letter height	180 (54.86)
CMS Signs	600 (182.88)
Arrowhead CMS	600 (182.88)
Speed Limit Signs (Normal, Work Zone, Feedback)	450 (137.16)
Lane Merge	450(137.16)

Using sign location and legibility distance, an influence area for each sign was specified for each time series trace. It was assumed that a driver may react at any point after the sign was legible and may react some distance downstream. For instance, a driver may see a work zone speed limit sign but not slow down until they have passed the sign. When using buffer distance of 80 meters downstream in previous section, almost every response point were located within 50 meter downstream distance. Using it as a reference, a distance of 50 meters downstream of each sign was included as an extent of the influence area. It shows the influence area of each sign as legibility distance of that sign upstream from sign location plus 50 meters downstream. Each response point was linked to the nearest corresponding work zone sign using the influence area for each sign. In some cases, the influence areas of two signs overlapped. In these cases, a separate node was created within the overlap area and when a response point fell within the overlapping area, it was assigned to the overlap area rather than an individual sign. Figure 9 below shows the detail methodology of connecting signs and response points.

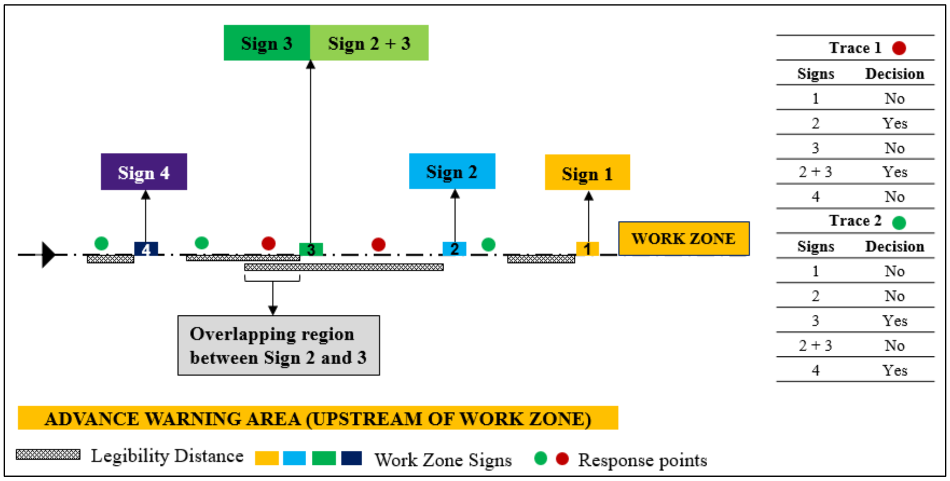


Figure 9 Methodology to combine work zone signs and reaction points

Based on the binary variable, a mixed effect logistic regression model was developed to find different factors like work zone signs, their location, types, vehicle speed, environmental factors, driver's information affecting driver's behavior at advance warning area.

2.4.1 Description of Data for the Model

Response points were identified for 299 time series traces corresponding to 142 unique drivers and 25 unique work zones on 4 lanes divided roadway with either lane or shoulder closures. As noted in the previous sections, 46 time series traces had no discernable response points and were not included in the model. Table 7 below shows the detail work zone sign locations and other additional information used for model development.

A total of 407 response points were identified from 253 traces. Only 67% of the response points were within the work zone sign influence area and were included in the model. Remaining 33% located outside the influence area were not used further assuming the cause of response not associated with the work zone signs or features.

First sign, speed limit and CMS were further classified based on their types ad summarized by distance of the signs from the start of work zone. Speed at each sign location or node was compared to the posted speed limit during that section which could have been either a normal or work zone speed limit and the difference was calculated. Driver characteristics such as age, gender, driving experience, and crash experience were summarized. Pavement condition at the time of sunny or cloudy or dry weather was coded as dry. Location shows the moving lane of the subject vehicle at the sign location. All other types of distraction events like cell phone, drinking / eating, passenger conversation, personal hygiene, and route planning were termed as distracted compared to no distraction event. For the glances, forward, left, right and rear view mirror glance were assumed normal glances associated with normal driving behavior compared to other glances as center console, steering wheel glances.

Table 7 Data summary

Variable		**Count**				
Total number of nodes (Y variable)		1529 (1 = 272, 0 = 1257)				
Total response points captured		272 (67% of 407)				
Work Zone (WZ) Type		**Count (Unique Traces)**	**Unique Driver ID**	**Unique WZ ID**		
Total		299	142	25		
Shoulder closed		82	56	8		
	Right side closed	13	10	1		
	Left side closed	69	50	10		
Lane closed		217	107	19		
	Right side closed	131	81	11		
	Left side closed	86	53	9		
Different Sign types		**Count (# of nodes)**	**Average distance to signs, meter**			
Total number of nodes		1529	Min.	Max.	Std. Error	Average
Static Work Zone Sign		413	57.96	2201.56	495.64	764.99
First Sign		270	9.45	4106.16	807.07	1569.42
	Enforcement	18	1687.74	2626.56	445.79	2164.51

Table 7 Continued

Different Sign types	Count (# of nodes)	Min.	Max.	Std. Error	Average
CMS (FSTypeCMS)	22	1287.74	1753.43	134.17	1567.10
Static Work Zone Sign (FSTypeWZ)	230	9.45	4106.16	847.78	1523.06
Speed Limit	310	7.11	4558.64	707.02	810.67
Normal (SpeedTypeNormal)	47	148.98	4558.64	689.73	1064.77
Work Zone (SpeedTypeWorkZone)	197	7.11	2697.36	799.11	827.86
Feedback (SpeedTypeFeedback)	66	110.65	670.22	108.67	578.44
CMS	120	164.42	1922.27	585.93	1155.12
Trailer	123	291.88	1922.27	546.38	1228.76
Overhead	19	164.42	1915.32	647.28	763.69
Emergency Sign	28	357.14	2510.60	347.32	1179.86
Overlapping Signs	208	74.73	4394.82	546.66	749.18
Lane Ends	180	136.03	593.55	103.04	307.29
Number of signs at each work zone		1	10	2.17	5.71
Number of signs passed		0	9	2.32	2.06
Distance, meter, DSM	1529	7.11	4558.64	699.53	898.03
Travelling speed					
Speed difference at First Sign, mph (Travelling – Posted Speed limit)	299	-10.84	33.63	8.36	11.71
Speed difference at all the Signs (Travelling – Posted Speed limit), mph, SD	299	-16.91	33.27	7.61	7.65
	Count	**Min.**	**Max.**	**Std. Error**	**Average**
Driver Age (Time of trip collection)	142	17	88	19.35	48.29
Driving experience	142	0	70	19.41	31.02
Sex (Male = 1, Female = 0)	70				
	0	**1**	**2 or more**		
Number of violations	226	43	30		
Number of crashes	218	72	9		
Count					
Types of Vehicle (Car = 1)	206 / Car	20 / Pickup Truck	64 / SUV	9 / Van	
Day vs Night (Day = 1)	242				
Pavement Condition (Dry = 1)	273				
Location of vehicle (Right = 1)	993				
Distracted = 1	130				
Normal glances = 1	1493				

2.4.2 Final Model

A mixed effect logistic regression model was used to assess the likelihood that a driver would respond to a particular work zone feature. Response points were identified for each time series trace as described in the previous section. The model included one observation for each work zone feature (node) for each time series trace. As a result, if a driver passed 10 work zone features in one time series trace, 10 observations were noted. If a response point was detected within the legibility distance defined for that feature, it was recorded as 1. If no response point was detected, it was recorded as 0. Driver ID and work zone ID were used as random effect in this model to account multiple samples from the same driver or work zone. A “glmer” function available in package “lme4” was used in R 3.5.1 to fit the model. The best fit model was selected based on the minimized Akaike Information Criterion (AIC). Correlations between the variables were checked prior to development of the model. Interaction between variables were considered in the model and their significance was checked. In addition, fitting of the model was also checked by visualizing residuals in R. Table 8 below shows the final model.

Table 8 Final model showing different factors affecting response point

Variable Description	**Variables**		**Estimate**	**Standard Error**	**p-value**	**Odds Ratio**
	(Intercept)		-0.835	0.628	0.184	0.434
Signs	Enforcement (EN)	Baseline: Static Work Zone Sign	-1.038	1.036	0.316	0.354
	First Sign (FS)		0.303	0.696	0.663	1.354
	Lane Ends (LE)		0.480	0.251	0.056	1.617
	Speed Limit (SL)		-1.396	0.586	0.017	0.248
	Changeable Message Sign (CMS)		0.850	0.329	0.010	2.340
	Overlapping (OV)		-0.198	0.260	0.447	0.820
Interaction of Sign Types	FS:FSTypeCMS		0.659	0.782	0.399	1.933
	FS:FSTypeWZ		-0.227	0.629	0.718	0.797
	CMS:CMS_NotActive		0.428	0.461	0.354	1.534
	SL:SpeedTypeWorkZone		1.881	0.554	0.001	6.559
	SL:SpeedTypeFeedback		1.720	0.611	0.005	5.585
Effect of location of signs	Distance of signs, every 100 m		-0.038	0.016	0.019	0.963
	SL:DSM100		0.056	0.025	0.025	1.058
Effect of speed difference	SD in mph		0.051	0.011	0.000	1.052
	FS:SD in mph		0.023	0.027	0.401	1.023
Other factors	Location Right (Right = 1, Left = 0)		-0.027	0.152	0.857	0.973
	Type of WZ (Lane Closure = 1, Shoulder Closure = 0)		-1.065	0.235	0.000	0.345
	Day (Day = 1, Night = 0)		-0.020	0.191	0.918	0.980
	Years of driving less than 5		0.170	0.159	0.283	1.186
	Gender (Male = 1, Female = 0)		-0.228	0.141	0.106	0.796
Distraction and Glance	Distracted = 1		-0.553	0.299	0.064	0.575
	Normal Glance = 1		-0.188	0.498	0.706	0.829

The odds ratio (OR) is the likelihood of a response point occurring for a particular type of sign using static work zone signs as a reference. The terminology "driver response" or "response" to indicate the likelihood of a change point occurring signifies a driver reduced their speed when encountering the sign or work zone feature.

Effect of First Sign on driving behavior was not found to be statistically significant. Drivers at active CMS signs were more likely to show response compared to static work zone signs [OR = 2.340]. The statistical significance of the speed limit with odds ratio of 0.248 shows an effect of normal speed limit sign at the start of the advance warning area. The effect of speed limit signs on driving behavior significantly increases both for speed limit signs of work zone and feedback type with odds of 6.559 and 5.585 respectively. Odds ratio of lane ends sign though not statistically significant (p close to 0.05) was more than 1.6.

For other types of signs (except speed limit), odds of drivers showing response changes by 0.963 times for every 100 meter increase in the distance from the start of the work zone. However, the odds of speed limit sign on the driver's response increases by 1.058 with every 100 meter increase in the distance.

The speeding behavior of drivers at each work zone sign shows that odds of drivers showing response increases by 1.052 time or 5.2% with every one mile per hour increase in the driving speed over the posted speed limit. In particular, the model also shows that driver response behavior was not statistically significant with the drivers speeding behavior at the entry of first sign.

However, the types of work zone was found to be significant with drivers driving at the advance warning area of work zone with lane closure less likely to show response compared to at drivers driving at advance warning area of shoulder closure [OR = 0.345].

The significant difference in work zone types might be the effect on the driving behavior due to configuration of signs including the distance of First Sign, number of signs, types of signs rather than the work zone type itself. The location of subject vehicle whether travelling on right or left lane was also not found to have significant effect on the driving behavior. Similarly, other variables like gender, experience and time of a day were not found to have significant effect.

The result also shows that distracted driver though not statistically significant were less likely to show response at signs with odds of 0.575 [p = 0.064].

2.5 Conclusion and Discussion

The main purpose of this study was to analyze the driving behavior within the advance warning area. A methodology to detect speed change points, termed as response point in this study, was used.

The summary of response points by different work zone signs showed that drivers were more likely to response closer to the First Sign and Static Work Zone Signs. However, drivers responded farther to Changeable Message Sign and Speed Limit signs. It might be due to the legibility distance of a particular sign.

The result from mixed effect model showed that work zone related Speed limit signs, and CMS signs were found to be significantly affecting the driving behavior compared to the effect of static work zone signs. Comparing the odds ratio, drivers were twice more likely to response at speed limit, CMS and lane ends signs compared to static work zone signs. The condition where multiple signs were legible, termed as overlapping signs, was not found to have significant effect. Overall, first sign was also found not to have significant effect on the driving behavior.

Drivers were more likely to show response at speed limit with work zone type and feedback type compared to normal speed limit signs. Similarly, the effect of CMS activated sign was found to be significantly affect the driving behavior however, the effect of not activated CMS sign was not found to be significant. Overall First Sign was not found to have significant effect on the driving behavior.

With increase in the distance from the start of the work zone, drivers were less likely to show response at different work zone signs (except speed limit). However, drivers were more likely to show response at speed limit signs kept far away from work zone rather than the one kept near to the work zones. It might be the reason with speed limit of work zone type showing slightly higher odds ratio compared to speed limit of feedback type (usually kept near to the work zone).

In addition, drivers were more likely to show response at the time travelling over the posted speed limit at different work zone signs. However, drivers entering the advance warning area higher than the posted speed limit were not found to show response at First Sign.

Distracted drivers were less likely to show response to signs while drivers glancing behavior was not found to be effective.

2.6 Study Limitations

The study is also not without limitations. The brake activation variable was available in the time series file but due to some missing values in some traces, it was not always possible to use it as a variable of interest to detect response point. Using speed as a variable of interest, the study threw few numbers of traces due to many missing cells in the speed column. Only traces with high-speed accuracy were used for the analysis. Traces where the speed of subject vehicle was influenced by the forward vehicle were also dropped. Though planned at the beginning, the effect of presence of police car was not considered separately in the analysis due to limited sample size. In addition, the effect of different types of text displayed in CMS signs was not considered. Due to the quality of the video, it was not always possible to reduce the text information. Additionally location within the work zone will have some impact on whether a driver decreases speed. For instance, even in the absence of other countermeasures, drivers will decrease speed if needed to complete a lane change and merge. Due to sample size constraints, it was not possible to assess the impact of distance.

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2.8 References

AASHTO. American Association of State Highway and Transportation Officials. Washington, DC. 2004. A policy on geometric design of highways and streets. 896 p.

Af Wåhlberg, A.E. Driver celeration behaviour and accidents – an analysis, Theoretical Issues in Ergonomics Science, 9:5, 383-403, 2008. DOI: 10.1080/14639220701596722.

Bach, K.M., M. G. Jæger, M. B. Skov, and N. G. Thomassen. Evaluating Driver Attention and Driving Behaviour: Comparing Controlled Driving and Simulated Driving. British Computer Society, 2008.

Benekohal, R.F., A. Hajbabaie, J.C. Medina, M. Wang, and M. V. Chitturi. Speed Photo-Radar Enforcement Evaluation in Illinois Work Zones. Illinois Center for Transportation Series No. 10-064, 2010. UILU-ENG-2010-2004, ISSN: 0197-9191.

Benekohal, R.F., L. Wang, R. Orloski, and L.M. Kastel. Speed-Reduction Patterns of Vehicles in a Highway Construction Zone. Transportation Research Record 1352. 1992.

Brewer, M.A., G. Pesti, and W. Schneider. Improving Compliance with Work Zone Speed Limits. Transportation Research Record 1948. 2006.

Carlson, P.J., Fontaine, M.D., and Hawkins, H. G. Jr. Evaluation of Traffic Control Devices For Rural High-Speed Maintenance Work Zones. Report FHWA/TX-00/1879-1. Texas Transportation Institute. The Texas A&M University System College Station, Texas 77843-3135. October 2000.

Chen, Z., J. Yu, Y. Zhu, Y. Chen, and M. Li, "D3 >: Abnormal driving behaviors detection and identification using smartphone sensors," 2015 12th Annual IEEE International Conference on Sensing, Communication, and Networking (SECON), Seattle, WA, 2015, pp. 524-532.

Daniel, J., K. Dixon, and D. Jared. "Analysis of fatal crashes in Georgia work zones." Transp. Res. Rec., 1715, 18–23. 2000.

Dixon, K, and C. Wang. Development of Speed Reduction Strategies for Highway Work Zones. Atlanta, GA: Georgia Department of Transportation, Office of Materials and Research. 2002.

Edara, P., C. Sun, and Y. Hou. Evaluation of Variable Advisory Speed Limits in Work Zones. Midwest Smart Work Zone Deployment Initiative, Federal Highway Administration U.S. Department of Transportation 1200 New Jersey Avenue SE Washington, DC 20590. August 2013.

Facts and Statistics – Work Zone Safety. Work Zone Management Program. U.S. Department of Transportation, Federal Highway Administration. Last modified: July 10, 2017. Accessed on October 24, 2017. https://ops.fhwa.dot.gov/wz/resources/facts_stats/safety.htm.

Finley, M. D., J. Jenkins, and D. McAvoy. Evaluation of Ohio Work Zone Speed Zones Process. FHWA/OH-2014/10. Ohio Department of Transportation, Columbus, OH. 2014.

Finley, M.D., L. Theiss, N.D. Trout, and G.L. Ullman. Studies to Improve the Management of Regulatory Speed Limits in Texas Work Zones. Report No. FHWA/TX-09/0-5561-1. Texas Transportation Institute, College Station, Texas, October 2008.

Fryzlewicz, P. Wild binary segmentation for multiple change-point detection. Ann. Statist. 42, 2243-2281. 2014.

Garber, N. J., and M. Zhao. "Crash characteristics at work zones." Rep. No. VTRC 02–R12, Virginia Transportation Research Council, Charlottesville, VA. 2002.

Garber, N. J., and R. Gadiraju. Speed Variance and Its Influence on Accidents. AAA Foundation for Traffic Safety, Washington, D.C. 1981.

Garber, N. J., and T. H. Woo. Accident Characteristics at Construction and Maintenance Zones in Urban Areas. VTRC 90-R12. Virginia Transportation Research Council, Charlottesville. 1990.

Gerard-Merchant, P. G. F, D. E. Stooksbury, and L. Seymour. Methods for starting the detection of undocumented Multiple Changepoints. Journal of Climate 21:4887–4899. 2008.

Ha, T., and Z.A. Nemeth. “Detailed study of accident experience in construction and maintenance zones.” Transp. Res. Rec., 1509, 38–45. 1995.

Hall, J. W., and V. M. Lorenz. Characteristics of Construction Zone Accidents. In Transportation Research Record 1230, TRB, National Research Council, Washington, D.C., 1989.

Hall, J., and E. Wrage. Controlling Vehicles Speeds in Highway Construction Zones. Department of Civil Engineering, University of New Mexico, Albuquerque, NM.1997

Hallmark, S, O. Smadi, and A. Sharma. Evaluation of Work Zone Safety Using the SHRP 2 Naturalistic Driving Study Data. Phase I Final Report and Phase II Proposal. SHRP 2 Implementation Assistance Program. Center for Transportation Research and Education at Iowa State University’s Institute for Transportation, September 2015a.

Hallmark, S.L., N. Oneyear, S. Tyner, and B. Wang. Analysis of Naturalistic Driving Study Data: Roadway Departures on Rural Two-Lane Curves. SHRP 2, Transportation Research Board. Washington D. C., 2015b.

Hanscom, F. Effectiveness of Changeable Message Displays in Advance of High-Speed Freeway Lane Closures. Transportation Research Record 844. Transportation Research Board, National Research Council, Washington, D.C., 1982.

Harb, R., E. Radwan, X. Yan, A. Pande, and M. Abdel-Aty. “Freeway work-zone crash analysis and risk identification using multiple and conditional logistic regression.” J. Transp. Eng., 1345, 203–214. 2008.

Jackels, J. and D. Brannan. Work Zone Speed Demonstration in District 1A. Minnesota Department of Transportation, St. Paul, MN. 1988.

Kircher, K., and C. Ahlstrom. Minimum Required Attention: A Human-Centered Approach to Driver Inattention. Human Factors, 59(3), 471–484, 2016.

Kwon, E., D. Brannan, K. Shouman, C. Isackson, and B. Arseneau. Development and Field Evaluation of Variable Advisory Speed Limit System for Work Zones. Transportation Research Record: Journal of the Transportation Research Board, No. 2015, Transportation Research Board of the National Academies, Washington, 2007.

Lyles, R.W., W.C. Taylor, and D. Lavansiri. A Field Test and Evaluation of Variable Speed Limits in Work Zones. Transportation Research Board 83rd Annual Meeting Compendium of Papers. 2004.

Manual on Uniform Traffic Control Devices (MUTCD). (https://mutcd.fhwa.dot.gov/).

Matteson D. S., N. A. James. A nonparametric approach for multiple change point analysis of multivariate data. J Am Stat Assoc. 109(505):334–345. doi:10.1080/01621459.2013.849605. 2013.

Maze, T. Speed Monitor Display. Midwest Smart Work Zone Deployment Initiative, FHWA Pooled Fund Study. Washington, DC: Federal Highway Administration. 2000.

McCoy, P.T., J.A. Bonneson, and J.A. Kollbaum. Speed Reduction Effects of Speed Monitoring Displays with Radar in Work Zones on Interstate Highways. Transportation Research Record 1509: 65–72, 1995.

Meyer, E. Long-Term Effects of Radar-Activated Speed Display. Midwest Smart Work Zone Deployment Initiative, FHWA Pooled Fund Study. Washington, DC: Federal Highway Administration, 2003.

Miyajima, C et al., "Driver Modeling Based on Driving Behavior and Its Evaluation in Driver Identification," in Proceedings of the IEEE, vol. 95, no. 2, pp. 427-437, Feb. 2007.

Muggeo, V.M.R. Estimating regression models with unknown break-points. Statistics in Medicine 22, 3055–3071. 2003.

Muggeo, V.M.R. R Package to Fit Regression Models with Broken-Line Relationships. R News, Vol. 8, No. 1, 2008, pp. 20–25.

Paolo, P. and D. Sar. "Driving Speed Behaviour Approaching Road Work Zones on Two-Lane Rural Roads." Procedia - Social and Behavioral Sciences 53: 672-681. 2012.

Paulsen, R. J., J. C. Glennon, and J. L. Graham. Traffic Safety in Construction Zones. Rural and Urban Roads, Vol. 16, No. 10-71. 1978.

Pigman, J. G., R. A. Kenneth. Analysis of accidents in construction and maintenance work zones. Frankfort: Kentucky Transportation Research Program, 1988. Report Number UKTRP-88-13. Report Date 6-1988.

Reyes, A.L. and S.A.Khan. Examining Driver Behavior in Response to Work Zone Interventions: A Driving Simulator Study. Smart Work Zone Deployment Initiative, Pooled Fund Study, 2008.

Richards, S.H., R. C. Wunderlich, and C.L. Dudek. Field Evaluation of Work Zone Speed Control Techniques. In Transportation Research Record 1035, TRB, National Research Council, Washington, D.C., 1985. pp. 66 - 78.

Riffkin, M., T. McMurtry, S. Heath, and M. Saito. Variable Speed Limit Signs' Effects on Speed and Speed Violation in Work Zones. Report UT-08-01. Salt Lake City, UT: Utah Department of Transportation, 2008.

Saito, M., and J. Bowie. Efficacy of Speed Monitoring Displays in Increasing Speed Limit Compliance in Highway Work Zones. Report UT – 03.12. Brigham Young University Department of Civil and Environmental Engineering, Provo, UT, 2003.

Sayer, J. R., J.M. Devonshire, and C. A. C. Flannagan. Naturalistic driving performance during secondary tasks. Proceedings of the 4th International Driving Symposium on Human Factors in Driver Assessment, Training, and Vehicle Design: driving assessment 2007, p. 224-230.

Sorel, M., W. Sarasua, W. Davis, J. Ogle, and A. Dunning. Use of radar equipped portable changeable message sign to reduce vehicle speed in South Carolina work zones. Transportation Research Board 2007 Annual Meeting Paper. 2006.

Thompson, B. 2002. Evaluation of Radar-Activated Changeable Message Sign for Work Zone Speed Control. Technical Report 01-16. Augusta, ME: Maine Department of Transportation, Transportation Research Division.

Wang, C., K.K. Dixon, and D. Jared, "Evaluating Speed-Reduction Strategies for Highway Work Zones," Transportation Research Record: Journal of the Transportation Research Board, No. 1824, Transportation Research Board of the National Academies, Washington, D.C., 2003, pp. 44–53.

Worker Safety. Work Zone Management Program. U.S. Department of Transportation, Federal Highway Administration. Accessed on October 24, 2017. https://ops.fhwa.dot.gov/wz/workersafety/index.htm.

You, B., F. Qiao, and L. Yu, L. Drivers' Reaction of Warning Messages in Work Zone Termination Areas with Left Turn. Journal of Transportation Technologies, 6, 139-147, 2016. doi: 10.4236/jtts.2016.63013.

Zeeman, A.S., and M. J. Booysen, "Combining speed and acceleration to detect reckless driving in the informal public transport industry," 16th International IEEE Conference on Intelligent Transportation Systems (ITSC 2013), The Hague, 2013, pp. 756-761.

CHAPTER 3. ASSESSING DRIVING REACTION POINT OF MAINSTREAM TURNING VEHICLES AT RURAL UNSIGNALIZED INTERSECTIONS: A NATURALISTIC DRIVING STUDY

Revised from a paper to be submitted in Transportation Research Part F: Traffic Psychology and Behavior

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Abstract

Rural intersection crashes account for a large number of crashes in rural areas and can be particularly problematic since they have high approach speeds, are frequented by a variety of vehicles (e.g., farm equipment), and can have varying and inconsistently applied traffic control and countermeasures. While crash analyses are typically used to evaluate contributing factors, analyzing driving behavior can provide additional insight to safety issues and serve as a surrogate safety measure when crash analyses cannot be conducted. These surrogate measures include gap acceptance and stopping and braking behavior methods.

This study used naturalistic driving data to analyze the driving behavior of major approach turning vehicles at rural two-way stop controlled intersections. A methodology was developed to detect the location where drivers showed reaction to the upcoming intersection in order to complete a turning maneuver. This location was defined as a reaction point and was identified as a change in speed. The study identified the reaction point for a set of intersections using data for vehicles that turned from a major to minor approach. The analysis found that different factors (i.e., driver, environmental, and roadway) affected drivers' reaction upstream of an intersection.

The results from this study showed that right turning vehicles began reacting, in general, sooner than left turning vehicles. More than 70% of drivers showed a reaction within 300 meters upstream of an intersection for both types of turning maneuvers. Intersections with on-pavement marking upstream of the intersection were found to be associated with longer reaction distance, while posted intersection ahead warning signs showed a reverse effect. In addition, the study found driving speed at the reaction point also significantly impacted the initial point of reaction. Drivers who were traveling faster than the posted speed limit were associated with a reaction point farther upstream than vehicles traveling at the speed limit. Overall, the results showed that drivers' operating speed, visibility, pavement conditions, and intersection ahead signs significantly affected the reaction point. The result also provides an information on the sensitive zone upstream of the intersection at the major approach.

Keywords: Reaction Point, Turning Vehicles, Speed, Upstream of Intersection

3. 1 Introduction

3.1.1 Background

Rural intersection crashes account for around 30% of crashes in rural areas with more than 80% of rural intersections fatalities occurring at rural unsignalized intersections (Golembiewski & Chandler 2011). Crashes in rural areas are often severe because of higher approach speeds and longer emergency response times (Gonzales et al 2009). One of the major contributing crash factors at rural stop controlled intersections is inappropriate gap selection (Chovan et al. 1994, Preston et al. 2004). Another contributing factor is failure to yield, which is influenced by driver age (McGwin and Brown, 1999, Keay et al. 2009), speeding, vision obstruction, and inattention/distraction (Campbell et al. 2004).

3.1.2 Literature Review

3.1.2.1 Emergency Response Time

A study from Grossman et al. 1995 showed that emergency response times and transport times to be greater in the rural setting. EMS response times in rural areas was found around 1.6 to 2 times longer than those in urban areas (Gonzalez et al. 2009). Due to more emergency response time (EMR) resulting in delayed definitive care motor vehicle crash injury rates are higher in rural area compared to urban area (Zwerling et al. 2005). A study by Brown, 1979 showed positive association between ambulance response time and ratio of fatal to serious injuries. Out of total fatal crashes in 2013, 52.1% occurred at rural area compared to 47.8% in urban area (Traffic Safety Facts 2013). National statistics for 2013 showed that the average overall EMS response time (EMS notification to EMS arrival at crash scene) for fatal crashes was 12.5 minutes in rural areas and 7.14 minutes in urban areas. Over 4% of fatal crashes in rural areas had response times (EMS notification to EMS arrival) greater than 60 minutes while only 1% of fatal crashes in urban areas exceeded the 60 minute limit (Traffic Safety Facts, 2013).

3.1.2.2 Gap acceptance behavior of minor street traffic

Inappropriate gap selection has been found to be a major contributing cause of right angle crashes at rural intersections (Preston et al. 2004). Researchers studied the driving behavior of turning vehicles in minor road at priority intersections controlled by either stop or yield sign to find different factors that affect drivers' decision to either accept or reject an available gap when joining the main road. Factors like waiting time, intersection delay, driver's age and gender were found to be significant (Lord-Attivor and Jha, 2012). Gorjestani et al. 2010 did a macroscopic review of driver gap acceptance and rejection behavior at rural thru-stop intersections in the US to check minor stream vehicles gap acceptance behavior by types of maneuver, waiting time, and vehicle classification. Result from few studies showed that size of gap acceptance from the minor street traffic also depends on the types of turn (Beanland et al. 2013). Many research studies have been using critical gap analysis approach to model driver gap acceptance behavior at minor approach of stop controlled intersection (Patil and Pawar, 2014; Miller, 1972; Mason et al. 1990, Thapa et al. 2018). Deterministic and Probabilistic methods are largely used for critical gap analysis (Rakha et al. 2011).

3.1.2.3 Treatments at rural intersections

Various countermeasures have been used at both minor and major approaches to address rural intersection crashes, including additional stop sign delineation, traverse rumble strips, overhead flashing beacons, on-pavement markings, lighting, and intersection conflict warning systems. Some of the countermeasures installed at minor approaches are double stop sign (Polanis, 1999; Atkinson et al. 2014), Transverse Rumble Strips (Srinivasan et al. 2012) while countermeasures like overhead flashing beacons (Pant et al. 1992; Srinivasan et al. 2008), on-pavement marking (FHWA, 2008), Lighting (Neuman et al. 2003; Atkinson et al. 2014), and Intersection Conflict Warning System (Hallmark et al. 2017) are used to alert both minor and major approach road users. Table 9 below shows findings from few research studies regarding the effect of different countermeasures based on crash data.

Table 9 Effect of different countermeasures (Source: Oneyear et al. 2016)

Research Studies	Countermeasures	Findings
Pant et al. 1992; Srinivasan et al. 2008	Flashing Beacons	Reduced crashes from 11.9% to 19% for angle crashes
FHWA 2008b	On-Pavement Signing	Reduced total crashes by 15%
Carstens and Berns, 1984; Walker and Roberts, 1976	Lighting	49% reduction in nighttime crashes at rural intersections with lighting
Gan et al. 2005	Advance Warning Signs at minor approach	Reduced crashes by 40%
Sorenson, 2011	Intersection Conflict Warning Systems	Reduced crashes on average by 51%

3.1.2.4 Different Approaches for Safety Evaluation

The most popular approach for assessing the effectiveness of countermeasures is to conduct a crash analysis (Polanis, 1999; Pant et al. 1992; Srinivasan et al. 2008). However, due to low volumes at rural intersections and the random nature of crashes, it can be difficult to isolate the impact of either intersection characteristics or applied countermeasures. Additionally, crash analyses are not able to capture driver behaviors such as approach speed or driver distraction. Other widely used methods to analyze driving behavior are gap acceptance behavior both for turning vehicles from minor approach (Solberg and Oppenlander, 1966; Cooper et al. 1976; Fitzpatrick, 1991; Alexander et al. 2007; Beanland et al. 2013, Thapa et al. 2018) and turning vehicles (especially left turning) from major approach (Spek et al. 2005; Devarasetty et al. 2012; Zhou et al. 2015), and stopping behavior (Harder et al. 2006; Woldeamanuel, 2012; Hallmark et al. 2017).

Several studies have used braking behavior to identify the point at which a driver begins to respond to the upcoming intersection as a safety surrogate. Bao & Boyle 2008 evaluated braking behavior approach for different ages of drivers at stop controlled approaches of rural intersections. A total of 60 participants drove a 2002 Ford Taurus, which was instrumented with cameras and a data receiver. The study used speed, braking force, and throttle position to evaluate driving performance of left, right, and through moving traffic from the minor approach. Montella et al. 2011 recruited 23 participants in a driving simulator in Naples, Italy, to assess different intersection countermeasures along a major road at rural intersections. Participants drove a series of intersections and metrics such as speed, deceleration, and lateral position were used to evaluate driving behavior.

Oneyear et al. 2016 analyzed braking behavior for major and minor approach vehicles at stop controlled rural intersections using the Second Strategic Highway Program (SHRP2) naturalistic driving data (NDS). They used the reaction point—defined based on initiation of braking—to the upcoming intersection as a dependent variable and developed the model using drivers' age, turn types, and various countermeasures at intersections as independent variables. The model was able to predict the distance upstream drivers needed to react to the upcoming intersections. However, the sample size was limited.

3.2 Methodology

3.2.1 Objectives

This paper summarizes research that evaluated the reaction point for drivers making a left or right turn from a major approach at rural two-way stop controlled intersections. Location of reaction point provides sensitive zone upstream of the intersection at the major approach. The reaction point was identified using a change point methodology. Driver information, roadway characteristics, advanced warning signs, and other information like pavement conditions and time of data were summarized, and a model was created to predict the likelihood of a distance-based driver reaction at a major approach at a rural intersection, which was then modeled using a linear mixed model. It was initially assumed drivers responding farther from the intersection are more likely to be a cautious drivers and less likely to involve in the crashes.

3.2.2 Data

The study utilized data from the SHRP2 NDS and Roadway Information Database (RID). The SHRP2 NDS is the largest and most comprehensive NDS undertaken to date. Data were collected from over 3,000 male and female volunteer passenger vehicle drivers (ages 16 to 98), with most drivers participating between one and two years. Participants were included from sites in six US states: Florida, Indiana, New York, North Carolina, Pennsylvania, and Washington.

Data, such as speed, acceleration, braking, and lateral position, were collected in-vehicle using a data acquisition system (DAS) and reported at 0.1 second intervals (time series). Video views of the forward roadway, rear roadway, driver face, and over the driver's shoulder were also collected. Global Positioning System (GPS) data was included as data variables and allowed spatial matching with roadway features. The SHRP2 NDS data is stored at a secure enclave at the Virginia Tech Transportation Institute (VTTI).

Detailed roadway characteristics were collected in tandem for about 12,000 centerline miles within the study sites. The RID also secured data from existing data sources such as state departments of transportation (DOTs) and the Highway Performance Monitoring System. This included roadway characteristics, traffic volume, and other supplemental data, which covered most roadways for the study site in each state. Figure 10 below shows the sample trace from major to minor turning vehicle at four way stop controlled intersection.

Figure 10 Time series data overlain on the major approach (turning vehicles) of four way stop controlled (image source: ESRI, VTTI)

A number of rural intersections within the SHRP2 study areas were identified using the RID. Identified intersections were narrowed to those where time series data for multiple drivers was present. This resulted in 29 intersections in five states. Time series data and the forward roadway video were requested and 449 viable traces were available along the major intersection approach for the study intersections. A trace is one trip through the intersection by one driver. Seventy nine unique drivers were included.

Intersection characteristics, such as number of lanes, presence of turn lanes, type of intersection, and presence and type of countermeasures, were either queried from the RID or manually extracted from the forward roadway video. Time of day and roadway surface conditions (e.g., wet versus dry) were also coded from the forward video.

3.2.3 Study Section

The study focused on rural two-way stop controlled intersections. No information was available that defined the likely intersection influence area. As a result, an analysis area was defined based on the location of intersection ahead warning signs and assuming a stopping sight distance on the major approach speed limit. In most cases, around 2,500 feet (762 meters) upstream of the intersection was considered to be of sufficient distance to capture driver reaction to the upcoming intersection, and, as a result, time series data was extracted for this distance. The study evaluated 79 drivers at 29 intersections. Figure 11 shows the study section upstream of intersection at the major approach.

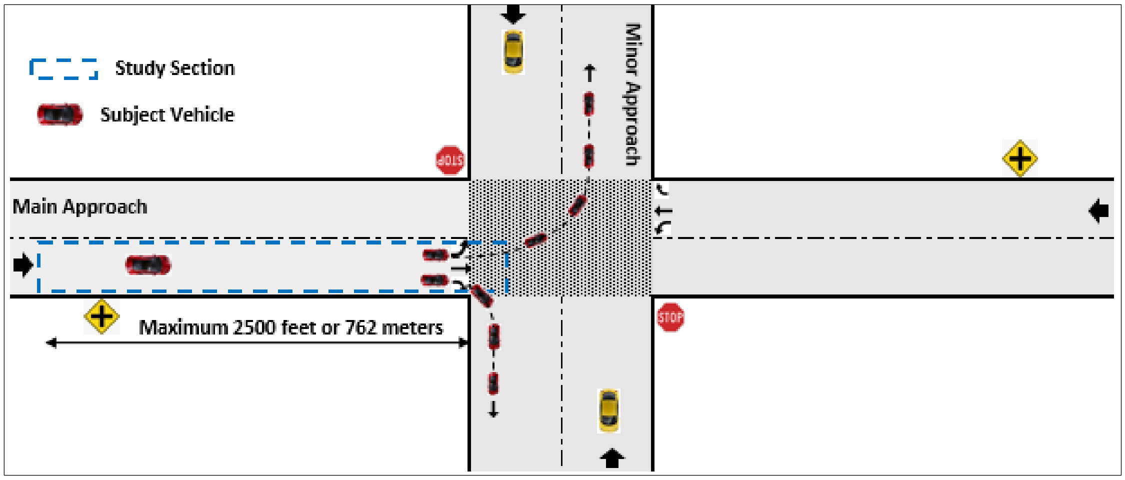

Figure 11 Study section upstream of main approach

3.2.4 Change Point Methodology

A model was developed to identify the reaction point for each individual trace using time series data within 2,500 feet (762 meters) of the intersection. The reaction point is defined as the point where drivers showed their first reaction to the upcoming intersection by starting to decrease speed in order to smoothly complete a turning maneuver. A change point model based on a piecewise linear regression approach was used to detect the reaction point.

To detect reaction point individual models were developed for each time series trace using speed as a dependent variable. “Segmented” package in R was used to fit the linear regression model in each interval. The model used for this package is as follows: $Y = \beta 0 + \beta 1 D + \beta 3 (D-D^*)$, where: Y is the dependent variable for each model; D is distance upstream from beginning of the intersection (negative value) which is measured from the junction of major and minor approach; and D* is the change or reaction point (the distance at which the driver first reacts to the intersection). The reaction point is detected if there is a significant difference in the slope of the fitted models [Muggeo 2008].

Using reaction point information from individual time series trace, a linear mixed effect model was developed to assess the characteristics associated with location of reaction point which was used as a dependent variable. A unique ID was assigned to each driver and intersection to account for repeated measures. Independent variables included driver characteristics (i.e. age, gender), intersection characteristics (number of lanes, type of control), countermeasures (i.e. lighting), intersection skew angle, vehicle speed at the reaction point (first reaction point), posted speed limit, weather factors on reaction point locations.

3.3 Analysis

A linear mixed effect model was developed to assess the characteristics associated with location of the reaction point. The reaction point is defined by identifying the first major change in slope of speed along the upstream intersection approach. The methodology and analysis are presented in the following sections.

3.3.1 Identification of Reaction Point

Time series data were correlated to distance upstream of the intersection, and a cumulative plot of the 449 traces used in this study is shown in Figure 12. The traces were from vehicles in free flow conditions either turning left (178 traces) or right (271 traces) from the major to minor approach at rural stop controlled intersections. As noted, the majority of drivers began slowing between 50 to 300 meters upstream of the intersection. Point zero in the figure shows the start of the intersection. As described earlier, it is measured from the junction of major and minor approach roadway.

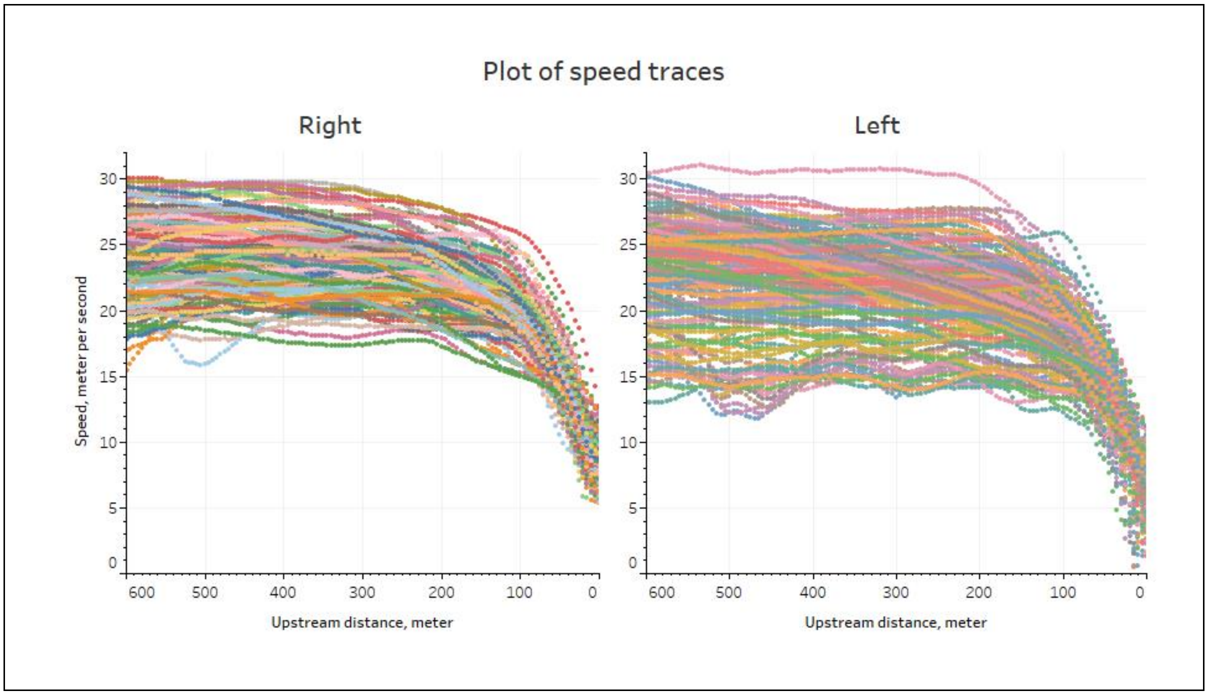

Figure 12 Plot of speed profile traces

A review of the individual fitted models suggest driver reaction can be categorized into two general profiles. One set of drivers showed a reaction at a single point and then decreased speed before making a turn, while others slowed multiple times prior to making the turn. As noted in Fig. 3 (top), the trace shows a significant change in speed around 150 meters followed by a sharp decrease in speed, while Figure 13 (bottom) illustrates initial change around 500 meters followed by a more moderate decrease and then another significant decrease around 150 meters.

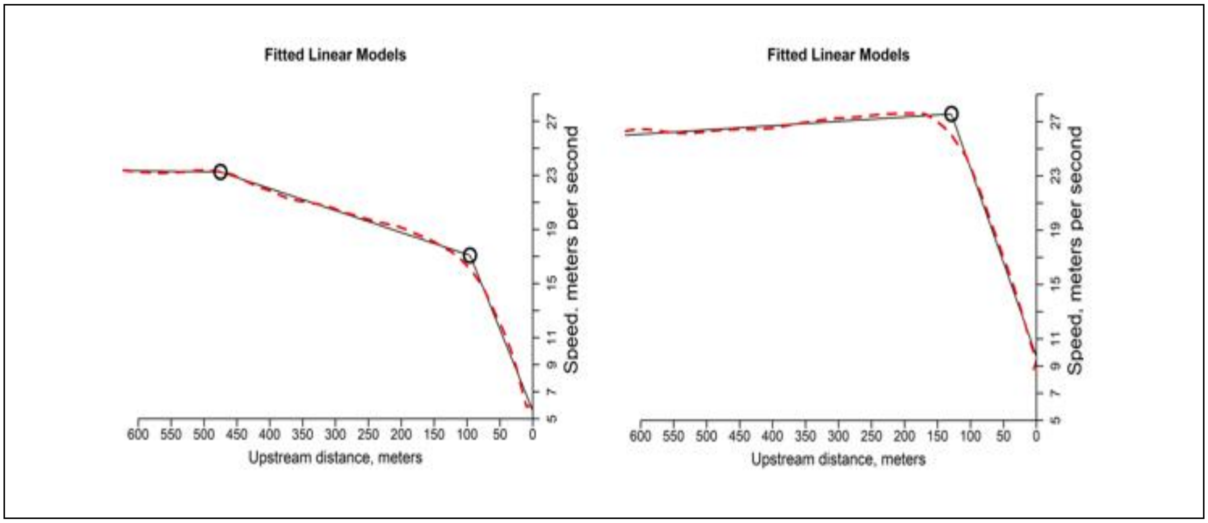

Figure 13 Two different speed profiles

Since the objective of the study was to assess the point at which a driver begins reacting to the intersection, the first reaction point was selected as the point of interest.

3.4 Result

3.4.1 Average Location of Reaction Points

Table 10 shows the results for the change point model for both types of turn. It shows that both left and right turning vehicles showed reaction to the system almost around the same distance upstream of the intersection.

Table 10 Reaction point result by types of turn, in meter

Type	Count	Minimum	Maximum	Mean, meter	SD
All	449	64.10	717.38	249.92	117.60
Left	178	64.10	717.38	238.31	123.10
Right	271	69.19	659.16	257.55	113.50

Figure 14 shows the distribution of change point results by 50 meter bins. For instance, 15.5% of right turning vehicles had the first reaction point within 150 to 200 meters upstream of the corresponding intersection. As noted, more than half of vehicles for both turning movements showed reaction within 300 meters of the intersection.

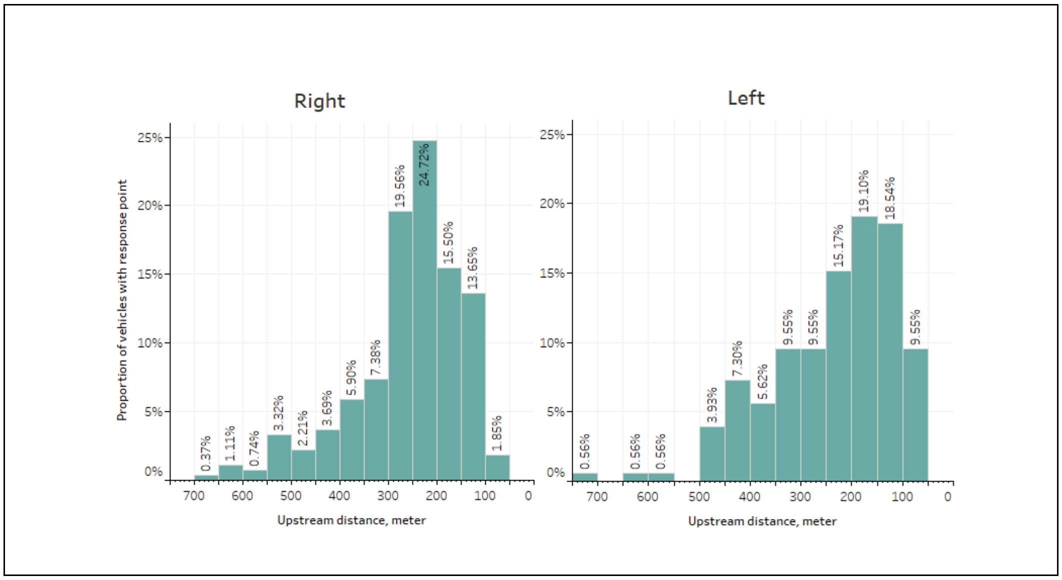

Figure 14 Distribution of detected reaction points

Table 11 shows the percentile distribution of the reaction distance. For instance, 95th percentile distance of 458.47 meter for the left turning vehicle shows the 95% of the traces showed reaction distance of 458.47 or lower and only 5% of the traces showed reaction distance of more than that value.

Table 11 Percentile distribution of the reaction distance, in meter.

	Reaction distance at different percentiles						
Type	**5h**	**10th**	**25th**	**50th**	**75th**	**90th**	**95th**
All	100.66	117.11	161.47	229.78	307.87	415.73	486.38
Left	91.49	101.58	144.15	207.58	311.02	420.01	458.47
Right	114.80	123.40	179.25	240.96	298.51	414.29	501.09

3.4.2 Reaction Point Model

A linear mixed effect model was developed to assess the characteristics associated with the location of the reaction point, which was used as a dependent variable. A unique ID was assigned to each driver and intersection to account for repeated measures. Independent variables included driver characteristics (e.g., age, gender), intersection characteristics (e.g., number of lanes, type of control), countermeasures (e.g., lighting), intersection skew angle, vehicle speed at the reaction point (first reaction point), posted speed limit, and weather factors on reaction point locations. The “lmer” function in the lme4 package in R was used to develop the model. Models were compared using Akaike information criterion (AIC) and the best fit model was selected. In addition, fitting of the model was also checked by visualizing residuals in R. Correlations between the variables were checked prior to development of the model. Interaction between variables were considered in the model and their significance was checked. In addition, fitting of the model and normality was checked by visualizing residuals in R.

Table 12 shows a summary of the data set used for this study. A total of 449 speed traces from 79 drivers at 29 different intersections were used to develop the model. The available data were summarized under different headings: Time of Day, Pavement Condition, Driving Characteristics, Intersection Characteristics, and Driver Information.

Pavement condition was coded as wet at the time of raining, and snowing (limited sample). At the time the turning vehicles stopped at the intersection waiting for the through moving vehicles from opposite site, it was coded as “Stopped for crossing traffic”. “Skewness” was defined as the angle between the major approach to the turning minor approach. Speed of the vehicles were measured at the reaction point and then compared to the posted speed limit. The difference was then used as an independent variable in the model. The traffic scenario at intersection at the time the subject vehicle was at the response point was coded. The scenario represent the presence of minor approach vehicles waiting for the safe gap, movement turning minor approach vehicles, and presence of turning or through moving major approach vehicles. Drivers’ characteristics were extracted from the NDS data source.

Table 12 Summary of the available data

Variable		Count	Minimum	Maximum	Mean	SD
Dependent variable, meters	(Reaction Point location)	449	64.104	717.38	249.28	118.1
Unique Driver ID		79				
Unique Intersection ID		29				
Time of a day						
Day		361				
Night		88				
Pavement Condition						
Dry		372				
Wet		77				
Driving Characteristics						
Stopped for crossing traffic (Yes = 1, No = 0)		11				
Speed Limit (miles per hour)		449	30.00	55.00	44.72	5.09
Skewness, degree	90	239				
	> 90	127				
Driving Characteristic						
	< 90		83			
Speed over the posted speed limit at reaction point (Driving speed – Posted speed limit), mph		449	-17.84	28.62	5.74	7.87
Types of Turn	Left	178				
	Right	271				
Intersection Characteristics						
In Curve (Yes = 1, No = 0)		114				
Slope of approach (Negative slope = 1, 0)		185				
Treatment			# of intersections			
	Flashing Beacon	74	3			
	Multilane	15	1			
	No Pavement Marking	8	1			
	On Pavement Marking	28	2			
Separate Turn Lane	Right Turn	28				
	Left Turn	108				
Location of warning signs, meter		398	71.33	360.72	226.77	68.64
Intersection Warning Sign (No = 1)		42				
Traffic Scenario at Intersection						
Presence of minor street vehicle, through moving vehicles at the time vehicle showed response (Yes =1, No = 0)		135				
Driver Information						
Years of driving, years		449	1	71	32	20
Number of Violations	0	396				
	1	37				
	2 or more	16				
Number of Crashes	0	367				
	1	44				
	2 or more	38				
Sex	Female	306				
	Male	143				

Results are provided in Table 13. As noted, drivers initially travelling above the posted speed limit were likely to have a reaction point farther from the intersections. For instance, for every 1 mile per hour driving over the posted speed limit at the reaction point, the reaction distance increased by 8.61 meters. There was no significant difference in the reaction distance for left and right turning vehicles. For every mile increase in the posted speed limit of the major approach, it increased the reaction distance by 10.51 meters. Presence of intersection ahead warning signs decreased the reaction point by 69.91 meters while the presence of on-pavement markings increased it by 67.75 meters. Additionally, the presence of a flashing beacon decreased the reaction point by 7.72 meters. In case of multilane major approach, the reaction point decreased by 39.81 meters. Additionally, the reaction point increased by 42.92 meters when wet pavement was present compared to dry pavement. The reaction point was 54.92 meters shorter in daytime compared to nighttime. Other driving variables like age, number of violations were not found significant in the model.

Table 13 Result of the final model

Parameters (Fixed Effect)	**Estimate**	**Standard Error**	**p-value**
(Intercept)	- 177.43	78.93	0.024
Driving characteristics			
Speed over the posted speed limit at Reaction point, mph	8.61	0.75	0.000
Types of Turn (Left = 1, Right = 0)	- 2.63	15.11	0.862
Intersection Features			
Posted Speed Limit, mph	10.51	1.72	0.000
Intersection Ahead Warning Signs (Yes = 1, No = 0)	- 69.61	26.85	0.008
Treatments			
Flashing Beacon at Intersection (Yes = 1, No = 0)	- 7.72	30.83	0.802
On-Pavement Marking upstream of Intersection (Yes = 1, No = 0)	67.75	32.43	0.036
Major approach features			
Multilane Major Approach (Yes = 1, No = 0)	- 39.81	48.75	0.414
No Pavement lane line (Yes = 1, No = 0)	- 1.44	54.36	0.978

Table 13 Continued

Parameters (Fixed Effect)	Estimate	Standard Error	p-value
Others			
Day Time (Day = 1, Night = 0)	- 54.92	11.54	0.000
Pavement Wet (Wet = 1, Dry = 0)	42.92	11.64	0.000
Years of driving	12.66	18.92	0.504
Random Effect	**Groups**	**Variance**	**SD**
	Driver ID	1064	32.62
	Intersection ID	1174	34.27
	Residual	7575	87.03
Number of observations: 449, Unique Diver ID: 79; Unique Intersection ID: 29			

3.5 Conclusion and Discussion

The study identified the first driver reaction point upstream of the intersection for drivers turning right or left from a major to minor approach. The reaction point was identified through a change point methodology using time series data from the SHRP2 NDS. A mixed linear effect model was used to assess the relationship between the initial reaction point and other characteristics.

In general, over 70% of drivers began reacting to the intersection around 300 meters upstream of the intersection for both left and right turn maneuvers. Model results also indicated that driving speed was found to positively correlate with the initial reaction point (i.e., drivers began reacting sooner). In addition, results also showed that drivers reacted sooner during the nighttime than daytime (54.92 meters) and when the pavement was wet compared to dry (42.92 meters). Additionally, the presence of an intersection warning ahead sign decreased while presence of on-pavement markings increased the initial point of reaction. The opposite reaction to two countermeasures that approximately convey the same information was puzzling. The study found no significant effect of overhead flashing beacons. The other intersection features like multilane approach compared to single lane and lanes with no pavement lining were not found to affect the reaction location. Overall, the results showed that drivers' operating speed, and a few specific treatments, were the most significant factors affecting reaction location. It clearly supports the installation of posted speed limit and intersection ahead warning signs upstream of intersections. However, the sample size was limited and inclusion of additional drivers and a larger sample of intersections is a planned next step.

3.6 Study Limitations

Significant number of traces were removed from the analysis due to the subject vehicle following too closely to the vehicle ahead as only free flow vehicles were considered for the analysis. In addition, some intersections were only associated with the limited traces. The study also could not cover different types of treatments applied at major approach due their unavailability in the available data set. Some of the speed traces were available with excessive noise and were removed from the analysis. Due to this reason the study did not focus on the effectiveness of the countermeasure, rather consider other driving factors to evaluate their effect.

3.7 Acknowledgment

The team would like to thank the Federal Highway Administration (FHWA) and the Iowa Department of Transportation for funding this research, the Virginia Tech Transportation Institute for their assistance in obtaining the SHRP2 data, and the Center for Transportation Research and Education (CTRE) at Iowa State University for providing the RID data.

3.8 References

Alexander, J., P. Barham, and I. Black. Factors influencing the probability of an incident at a junction: results from an interactive driving simulator. Accident Analysis & Prevention. Volume 34, Issue 6, November 2002, pp. 779-792.

Atkinson, J.E., B. E. Chandler, V. Betkey, K. Weiss, K. Dixon, A. Giragosian, K. Donoughe, and C. O'Donnell. Manual for Selecting Safety Improvements on High Risk Rural Roads. Federal Highway Administration, Office of Safety, Washington DC, 2014.

Bao, S., and L. N. Boyle. Driver Performance at Two-way Stop-controlled Intersections on Divided Highways. Transportation Research Record: Journal of the Transportation Research Board, No. 2069, 2008, pp. 26–32.

Beanland, V., M. G. Lenné, N. Candappa, and B. Corben. Gap acceptance at stop-controlled T-intersections in a simulated rural environment. Transportation Research Part F: Traffic Psychology and Behaviour, 20, 2013, 80-89. doi: http://dx.doi.org/10.1016/j.trf.2013.05.006.

Brown, D. B. Proxy measures in accident countermeasure evaluation: a study of emergency medical services, Journal of Safety Research 1979, p 11, 37-41.

Campbell, B.N., J.D. Smith, and W.G. Najim. Analysis of Fatal Crashes Due to Signal and Stop Sign Violations. National Highway Traffic Safety Administration, US Department of Transportation. DOT HS 809 779. Sept. 2004.

Carstens, R. L. and L. D. Berns. Roadway Lighting on Secondary Roads in Iowa. Iowa Department of Transportation. Ames, IA, 1984.

Chovan, J.D., L. Tijerian, J. H. Everson, J. A. Pierowicz, and D. L. Hendricks. Examination of intersection left turn across path crashes and IVHS countermeasures (DOT HS 808 154). National Highway Traffic Safety Administration, 1994.

Cooper, D.F., W. Smith, and V. Broadie. Traffic Studies at T-Junctions, 1. The Effect of Approach Speed on Merging Gap Acceptance. Traffic Engineering and Control, Vol. 17, No. 6, June 1976, pp. 256-257.

Devarasetty, P.C., Y. Zhang, and K. Fitzpatrick. Differentiating between Left-Turn Gap and Lag Acceptance at Unsignalized Intersections as a Function of the Site Characteristics. Journal of Transportation Engineering 138(5), 2012, pp. 580-588.

FHWA. 2008b. Safety Evaluation of STOP AHEAD Pavement Markings. Tech Brief. Federal Highway Administration, Research, Development, and Technology. Turner-Fairbank Highway Research Center, McLean, VA.

FHWA. Two Low-Cost Safety Concepts for Two-Way STOP-Controlled, Rural Intersections on High-Speed Two-Lane, Two-Way Roadways. Summary Report. Federal Highway Administration, Research, Development, and Technology. Turner-Fairbank Highway Research Center, McLean, VA, 2008.

Fitzpatrick, K. Gaps accepted at stop-controlled intersections. Transportation Research Record 1991, 1303, pp. 103-122.

Golembiewski, G.A., and B. Chandler. Intersection Safety: A Manual for Local Rural Road Owners. Federal Highway Administration, Washington, DC, FHWA-SA-11-08, 2011.

Gonzalez, R.P., G.R. Cummings, H. A. Phelan, M. S. Mulekar, and C. B. Rodning. Does Increased Emergency Medical Services Prehospital Time Affect Patient Mortality in Rural Motor Vehicle Crashes? A Statewide Analysis. The American Journal of Surgery, 2009, Vol. 197, pp. 30-34.

Gorjestani, A, A. Menon, P. M. Cheng, B. Newstrom, C. Shankwitz, and M. Donath. Macroscopic Review of Driver Gap Acceptance and Rejection Behavior at Rural ThruStop Intersections in the US – Data collection Results in Eight States: CICAS-SSA Report #3. US Department of Transportation Research and Innovative Technology Administration, Washington, DC., 2010

Grossman, D. C., L. F. Hart, F. P. Rivara, R. V. Maier, and R. Rosenblatt. From roadside to bedside: regionalization of trauma care in a remote rural county. J Trauma 1995; Jan; 38 (1):14-21.

Hallmark, S.L., N. Hawkins, R. Thapa, S. Knickerbocker, and J. Gaspar. Evaluation of Intersection Collision Warning Systems in Minnesota. Minnesota Department of Transportation (MN/RC 2017-38), October 2017.

Harder, K.A., Bloomfield, J.R., and Chihak, B.J. Stopping Behavior at Real-World Stop-Controlled Intersections With and Without In-Lane Rumble Strips, Report No MN/RC-2006-42, Submitted to Minnesota Department of Transportation, 2006, St. Paul, MN.

Keay, L., S. Jasti, B. Munoz, K.A. Turano, C.A. Munro, D.D. Duncan, K.Baldwin, and D.J. Baneen-Roche, E.W. Gower, and S.K. West. Urban and rural differences in Older drivers Failure to Stop at Stop Signs. Accident Analysis and Prevention. Vol. 41, Issue 5. September 2009. pp. 995-1000.

Lord-Attivor, R., and M. K. Jha, Modeling gap acceptance and driver behavior at stop controlled (priority) intersections in developing countries, Proceedings of the 6th WSEAS international conference on Computer Engineering and Applications, and Proceedings of the 2012 American conference on Applied Mathematics, p.29-38, January 25-27, 2012, Harvard, Cambridge.

McGwin, G. and D.B. Brown. Characteristics of traffic crashes among young, middle-aged, and older drivers. Accident Analysis and Prevention. Vol. 31, Issue 3. May 1999. pp. 181-198.

Miller, A. J. Nine Estimators of Gap-Acceptance Parameters. International Symposium on the Theory of Traffic Flow and Transportation, Berkeley, California, 1972.

Montella, M. Aria, A. D'Ambrosio, F. Galante, F. Mauriello, and M. Pernetti. Simulator evaluation of drivers' speed, decelration and lateral position at rural intersections in relation to different perceptual cues. Accident Analysis and Prevention, Vol. 43, Issue 6, 2011, pp. 2072-2084.

Muggeo, V.M.R. R Package to Fit Regression Models with Broken-Line Relationships. R News, Vol. 8, No. 1, 2008, pp. 20–25.

Neuman, T.R., R. Pfeffer, K. L. Slack, K. K. Hardy, D. W. Harwood, I.B. Potts, D. J. Torbic, and E. R. Kohlman Rabbani. NCHRP Report 500: Guidance for Implementation of the AASHTO Strategic Highway Safety Plan, Volume 5: A Guide for Addressing Unsignalized Intersections. National Highway Cooperative Research Program, Washington DC, 2003.

Oneyear, N., S. L. Hallmark, and B. Wang. Evaluating the Relationship between the Driver and Roadway to Address Rural Intersection Safety using the SHRP 2 Naturalistic Driving Study Data. Iowa Department of Transportation and Federal Highway Administration (InTrans Project 13-476), 2016.

Pant, P.D., Y. Park, and S. V. Neti. Development of Guidelines for Installation of Intersection Control Beacons. Federal Highway Administration, Washington, DC, 1992.

Patil, G. R., and. S. Pawar. Temporal and Spatial Gap Acceptance for Minor Road at Uncontrolled Intersections in India. Transportation Research Record: Journal of the Transportation Research Board, No. 2461, Transportation Research Board of the National Academies, Washington, D.C., 2014, pp. 129–136. DOI: 10.3141/2461-16.

Polanis, S.F., Low-Cost Safety Improvements. Chapter 27 in The Traffic Safety Toolbox: A Primer on Traffic Safety. Institution of Transportation Engineers, Washington, DC, 1999, pp. 265-272.

Preston, H, R. Storm, M. Donath, and C. Shankwitz. Review of Minnesota's Rural Intersection Crashes: Methodology for Identifying Intersections for Intersection Decision Support. Minnesota Department of Transportation. St. Paul, MN. MN/RC-2004-31, 2004.

Rakha, H., S. Sadek, and I. Zohdy. Modeling Differences in Driver Left-Turn Gap Acceptance Behavior Using Bayesian and Bootstrap Approaches. 6th International Symposium on Highway Capacity and Quality of Service Stockholm, Sweden June 28 – July 1, 2011.

Solberg, P., and J. C. Oppenlander. Lag and Gap Acceptance at Stop-Controlled Intersections. In Highway Research Record 118, HRB, National Research Council, Washington, D.C, 1966, pp. 48-67.

Sorenson, W. Intelligent technology for stop-controlled intersections. Technology News, July–September 2011. Iowa Local Technical Assistance Program (LTAP), Institute for Transportation, Ames, IA.

Spek, A.C.E., P. A. Wieringa, and W. H. Janssen. Intersection approach speed and accident probability. Transp. Res. Part F: Traffic Psychol. Behav. 9, 2006, pp. 155–171.

Srinivasan, R., D. Carter, K. Eccles, P. Persaud, N. Lefler, C. Lyon, and R. Amjadi. Safety Evaluation of Flashing Beacons at STOP-Controlled Intersections. Federal Highway Administration Research, Development, and Technology. Turner-Fairbank Highway Research Center, McLean, VA, 2008, Publication No. FHWA-HRT-08-044.

Srinivasan, R., J. Baek, and F. M. Council. Safety Evaluation of Transverse Rumble Strips on Approaches to Stop-Controlled Intersections in Rural Areas. Highway Safety Information System Summary Report. Federal Highway Administration, Research, Development, 2012, Publication Number: FHWA-HRT-12-047.

Thapa, R., S. Hallmark, N. Hawkins, and S. Knickerbocker. Evaluation of Intersection Conflict Warning System: A Critical Gap Analysis. Transportation Research Record: Journal of the Transportation Research Board, 2018. https://doi.org/10.1177/0361198118777357

Traffic Safety Facts 2013: A Compilation of Motor Vehicle Crash Data from the Fatality Analysis Reporting System and the General Estimates System. National Highway Traffic Safety Administration National Center for Statistics and Analysis. U.S. Department of Transportation. Washington, DC 20590.

Woldeamanuel, M. Stopping Behavior of Drivers at Stop-Controlled Intersections: Compositional and Contextual Analysis. Journal of the Transportation Research Forum, Vol. 51, No. 3 (Fall 2012), pp. 109-123.

Zhou, H., N. E. Lownes, J. N. Ivan, P. E. Gårder, and N. Ravishanker. Left-Turn Gap Acceptance Behavior of Elderly Drivers at Unsignalized Intersections, Journal of Transportation Safety & Security, 7:4, 2015, pp. 324-344, DOI:10.1080/19439962.2014.976689.

Zwerling, C., C. Peek-Asa, P. S. Whitten, S.-W. Choi, N. L. Sprince, and M. P. Jones. Fatal Motor Vehicle Crashes in Rural and Urban Areas: Decomposing Rates into Contributing Factors. Injury Prevention, Vol. 11, No. 1, 2005, pp. 24–28.

CHAPTER 4. ASSESSING DRIVER REACTION OF MAINLINE THROUGH MOVING VEHICLES AT RURAL INTERSECTIONS: A NATURALISTIC DRIVING STUDY

Revised from a paper to be submitted in Transportation Research Part F: Traffic Psychology and Behavior

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Abstract

Crash statistics shows higher fatal crashes at rural intersections and it can be more problematic since rural intersections have higher approach speed and inconsistently applied traffic control measures. While crash analyses are typically used to evaluate contributing factors, analyzing driving behavior can provide additional insight to safety issues and serve as a surrogate safety measure when crash analyses cannot be conducted. Research studies have mostly used gap acceptance, stopping and braking behavior methods to analyze driving behavior of both major and minor approach vehicles with in the intersection. However, driving behavior of major approach through moving vehicles upstream of intersection is poorly understood.

This study used naturalistic driving data to analyze the driving behavior of major approach through moving vehicles at rural two-way stop controlled intersections. A suitable methodology was used to detect location, defined as a response point, where drivers showed response to the upcoming intersection by decreasing speed of ≥ 3 mph. By detecting if response point exist for vehicles at major approaches, a binary model was developed

including different roadway characteristics, driver information and other driving kinematics variable affecting drivers response upstream of intersections.

The result from this study showed that about 32% of drivers showed response to intersections upstream by decreasing speed by at least 3 miles per hour. Vehicles were more likely to show response to intersection at the time of presence of vehicles at the minor approaches. Non experienced drivers were found to be aware of the intersection ahead compared to experienced drivers. Drivers operating speed above 5 miles per hour were more likely to show response to the intersection. Intersections with intersection ahead warning signs were more likely to affect the driving behavior. This support the installation of intersection ahead warning signs installed upstream of the intersection.

Keywords: Response Point, Rural Intersection, Stop-Control

4.1 Introduction

4.1.1 Background and Literature Review

Rural intersections account for 30% of crashes in rural areas and 16% of fatalities in rural areas (IIHS, 2016). Rural intersection crashes are frequently a result of driver's failing to yield right of way. Failure to yield may be due to speeding which can result in failure to react in time or may be due to failure to recognize the presence of the intersection or traffic control due to sight distance issues or driver inattention. Retting et al. 2003 investigated crashes at stop-controlled intersections in four cities. They found that stop-sign violations accounted for about 70% of crashes.

Crashes in rural area are often severe because of higher approach speed, and longer emergency response time. A research study from Gonzalez et al. 2009 showed EMS response times in rural areas are around 1.6 to 2 times longer than those in urban areas. Another major contributing factor to rural intersection crashes is inappropriate gap selection (Chovan et al.

1994; Preston et al. 2004). Other contributing factors are failure to yield which is influenced by driver age (McGwin and Brown, 2003: Keay et al. 2009), speeding, vision obstruction, and inattention/distraction (Campbell et al. 2004).

Preston et al (2004) evaluated rural intersection crashes in Minnesota and found right angle crashes account for 15% of crashes on two-lane roadways and 18.4% at rural expressway intersections. They reported that right angle crashes result in a higher fatality or injury crash than for other crash types in rural areas and that gap selection is one of the predominant issues. Challenges in negotiating intersections are a function of failure to see or obey traffic control, perceive cross traffic, or judge the speed and distance of on-coming vehicles (McGwin and Brown, 1999; Caird et al. 2005; Guerriera et al. 1999). Rural intersection negotiation is exacerbated by high approach speeds resulting in significant speed differences between on-coming traffic on the major approach and those making a maneuver from the minor stop-controlled approach.

Although the behavior of the minor street (stop controlled) approach driver determines whether a potential crash occurs due to failure to yield or inappropriate gap selection, the speed and ability of a conflicting major street driver to respond is a critical factor in crash avoidance and severity if a crash occurs. Additionally the ability of a minor street driver to select a gap has been linked to the speed of major street traffic. Yan et al. 2007 evaluated the effect of speed of major stream traffic on gap acceptance of minor stream traffic in a driving simulator. Results showed the speed of major stream traffic is a significant factor in the gap accepted by minor stream traffic with drivers accepting smaller gaps (5.82 seconds) at higher speed major stream traffic compared to larger gaps (7.44 seconds) at lower speed major stream traffic. The result showed drivers are more sensitive to distance and position of major approach vehicle rather than its speed and is also supported by Davis and Swenson, 2004. In addition, Spek et al. 2006 developed a theoretical crash prediction model and found that the probability that a crossing vehicle collides with the major stream traffic can be expected to increase with increase in the speed of major approach traffic which also support the finding from Abou-Henaidy et al. 1994.

4.1.2 Objectives

Rural intersection crashes are particularly problematic due to high speed approaches, type of crash (right angle crashes tend to be more severe), and emergency response time in rural settings. As noted above, the driver on a minor stop controlled approach determines whether the potential for a crash exists but the speed and response behavior of conflicting major stream driver determines whether the crash can be avoided or the severity of the crash. However, driving behavior of major approach drivers is not well understood particularly since assessing crash contributing factors often focuses on the minor street driver.

The SHRP 2 naturalistic driving study data (NDS) provide a unique dataset to assess driver behavior under both safety critical and normal driving. The study described in this paper utilized the SHPR 2 NDS data to analyze the driving behavior of major approach drivers at rural two way stop controlled intersections. The main objective of this study was to determine whether major approach drivers responded to the upcoming intersection. Whether a driver has noticed and is alerted to an upcoming intersection does not necessitate a physical response since in the absence of a conflict, the major street driver is not expected to take any action. Awareness of the upcoming intersection is largely internalized. However, since mental alertness is difficult to measure in a NDS study, change in speed was used as a surrogate for driver reaction. It was assumed that drivers who slow have noted the upcoming intersection.

4.2 Data

The study utilized time series data from the SHRP 2 Naturalistic Driving Study (NDS) to assess changes in speed upstream of an intersection on the mainline (major) approach. The SHRP 2 NDS collected from over 3,000 male and female volunteer passenger vehicle drivers, ages 16–98 with most drivers participating between one and two years. Participants were included from sites in six US states: Florida, Indiana, New York, North Carolina, Pennsylvania, and Washington. Data, such as speed, acceleration, braking, and lateral position, were collected in-vehicle using a data acquisition system (DAS) and reported at 0.1 second intervals. These data are available as time series data and include GPS which allows them to be mapped to the corresponding roadway. Video views of the forward roadway, rear roadway, driver face, and over the driver's shoulder were also collected. The SHRP NDS are stored at a secure data enclave at the Virginia Tech Transportation Institute (VTTI).

Another project that was simultaneously conducted along with the SHRP 2 NDS study developed the SHRP2 Roadway Information Database (RID). Mobile data collection was conducted on over 12,500 center line mile across the six NDS states. Existing roadway and supplemental data acquired from public and private sources were also included in the RID. These data came from several sources including the NDS states' Department of Transportation (DOT), Highway Performance Monitoring System (HPMS), covering most roadways for each study state. In addition to that, supplemental data such as 511 data, construction projects data, and traffic volume were also collected to further strengthen the database.

A set of intersections were identified using the RID and associated characteristics such as speed limit, number of lanes, presence of turn lanes, type of intersection (i.e. 4-way, T), and presence and type of countermeasures were either queried from the RID or manually extracted from aerial imagery or forward roadway video. Countermeasures present at the intersections utilized included pavement marking with “Slow Down”, pedestrian crossing warning signs, and Intersection Warning Sign. As major approach vehicles do not have to stop at minor strop controlled intersections, fewer countermeasures are typically applied than for minor street approaches.

Rural intersections were manually identified from five different states (Indiana, New York, North Carolina, Pennsylvania, and Washington). Intersections were identified based on its characteristics, control and countermeasures. Data from 42 intersections were requested and a total of 3,855 traces were received (2,485 traces at two-way stop-controlled intersections and 1,370 traces at controlled T intersections). The available traces consisted of different movements (minor to major, major to major and major to minor, minor to minor approaches). As a result, only a subset were available for the analysis.

The study only selected traces with speed data accuracy of more than 90%. Vehicle speed was used as a surrogate for response to the upcoming intersection. In some cases, speed data were missing for several rows. Sample time series traces were only included when at least 90% of the speed data was present. In these cases, speed values for missing cells were linearly interpolated in R software. The interpolated data were then smoothed in R using a suitable smoother. Smoothing was done to avoid unnecessary noise in the speed profile. Time series traces with less than 90% of speed data available were excluded from the analysis

Each remaining trace was reviewed using the time series data and forward roadway video and the forward video was used to confirm turning movement (left, through, right), time of day, and roadway surface condition (wet versus dry). Since the intent was to assess how mainline drivers reacted to the presence of an intersection, only vehicles traveling through the intersection were included (no left or right turns). Additionally, only vehicles in free flow were included since a following vehicle is likely to be influenced by the lead vehicle and was not pertinent to whether a driver reacted to the presence of the upcoming intersection. For instance, a number of samples included situations where the subject vehicle was slowed by a leading vehicle executing at turn and were excluded from the analyses. Time series traces were also removed when an unusual scenario was present which may have caused the driver to slow in the vicinity of the intersection but was not likely to be related to the presence of the intersection (i.e. an animal was in the roadway). Ultimately, 223 traces from 27 unique drivers at 14 different intersections were considered for this study. The data were available from Indianapolis, North Carolina and Pennsylvania.

This study focused on high speed rural two-way stop controlled intersections. Data for each time series trace was mapped to the corresponding intersection. A section from 1,500 feet upstream of the intersection to a point 100 feet downstream of the intersection point was used as the study area for this analysis. The upstream distance was selected based on the advance placement of the warning sign according to Manual on Uniform Traffic Control Devices (MUTCD) where distance of warning signs in the speed reduction condition at a roadway of speed limit of 60 mph was mentioned as 1100 feet and 400 feet for a potential stop situation, a separate research study by (Montella et al. 2011) where they found speed reduction to be statistically significant around 250 meter (850 feet) upstream of intersection, and legibility distance for intersection warning signs. The downstream distance was considered in order to determine whether a vehicle turned at the intersection. Figure 15 shows a sample time series data overlain with an intersection.

Figure 15 Time series data overlain on the major approach of four way stop controlled (image source: ESRI, VTTI)

Table 14 shows the summary of the data used for this study. A total of 223 traces from 27 unique drivers at 14 different rural intersections (T and 4-way intersection) from three different states (Indianapolis, North Carolina and Pennsylvania) were used.

Table 14 Summary of traces used for the study

Total number of traces	**Unique Drivers**	**Unique Intersections**	**States**
223	27	14 (T-intersection = 9 and Four way intersection = 5)	IN = 3, NC = 205 and PA = 15)

4.3 Analysis and Results

Speed was used as a surrogate to indicate a driver acknowledged and responded to the presence of an intersection. The first step in the analysis was to develop response point for each time series trace. The times series data have a certain amount of noise. Identifying a response point as opposed to a fluctuation in the data can be difficult. As a result, a threshold was developed to indicate an actual change in speed had occurred. To identify the threshold, the literature was consulted. A study by Montella et al. 2011 showed that treatments used to reduce vehicles speed at major approaches of rural intersection were able to reduce a significant speed reduction starting from 250 m before the intersection in the range between 13 km/h (8.07 mph) and 23 km/h (14.29). Even without the speed reduction measures, the presence of intersection compared to no intersection scenario produced a statistically significant mean speed reduction of 16 km/h (9.95) at the center of intersection. In addition, Godavarthy et al. 2017 studied the effectiveness of different speed reduction measures at intersection approaches. At sites with intersections, the solar speed displays and mobile speed trailer were able to significantly reduce mean speed at major approaches from 1.7 miles per hour to 7.1 mph and from 2.5 to 7.1 mph respectively. Other countermeasures installed at the major approaches near to the intersections were also found to reduce the major approach speed to some extent: narrowing lane (average of 3 mile per hour) (Bared et al. 2008), interventions like innovative signage and large guide signs (11.8% to 44% reduction in speed with in 100 meter of intersection) (Harder et al. 2003). There are very few limited study available evaluating the driving behavior at major approaches of rural stop controlled intersections especially in terms of change in speed.

Thus based on the few past research studies (Montella et al. 2011; Godavarthy et al. 2017; Bared et al. 2008; Harder et al. 2003) and the trend of existing speed profile of different drivers, response point was defined as the point where drivers decreased speed by ≥ 3 miles per hour [1.341 meter per second] for at least 98 feet or 30 meter distance (based on normal deceleration rate). In addition, only statistically significant points were considered. A Davies test was used to check if detected change points were significant.

A cumulative plot of the 223 traces used in this study is shown in Figure 16 and show speed for the upstream section of the intersection. The traces used for this study were only from through moving vehicles in a free flow condition. To detect response points from all 223 traces, individual models were developed for each time series trace using speed as a dependent variable. “Segmented” package in R was used to fit the linear regression model. The model used for this package is as follows: $Y = \beta 0 + \beta 1\ D + \beta 3\ (D-D^*)$, where: Y is the dependent variable for each model; D is distance upstream from beginning of intersection (negative value); and D* is response point (the distance of response points). Response points were detected if there is a significant difference in the slope of the fitted models (Muggeo, 2008). Only detected response points satisfying the above threshold of ≥ 3 miles per hour were used for the analysis. The speed profile of two plots shown below were defined based on the traces with and without response point as every driver did not show response to the intersection ahead. Only 21 sample speed plot from each scenario (with and without) was used to plot the figure. It shows that the speed profile of vehicles showing response upstream of intersections were slightly inclined toward the intersection whereas the speed profile with traces not showing response point upstream either increased the speed or moved with uniform speed. As response point was defined as minimum as 3 mph, it is not visible in figure due to scaling of the axis but at least a pattern between two different speed profiles could be observed.

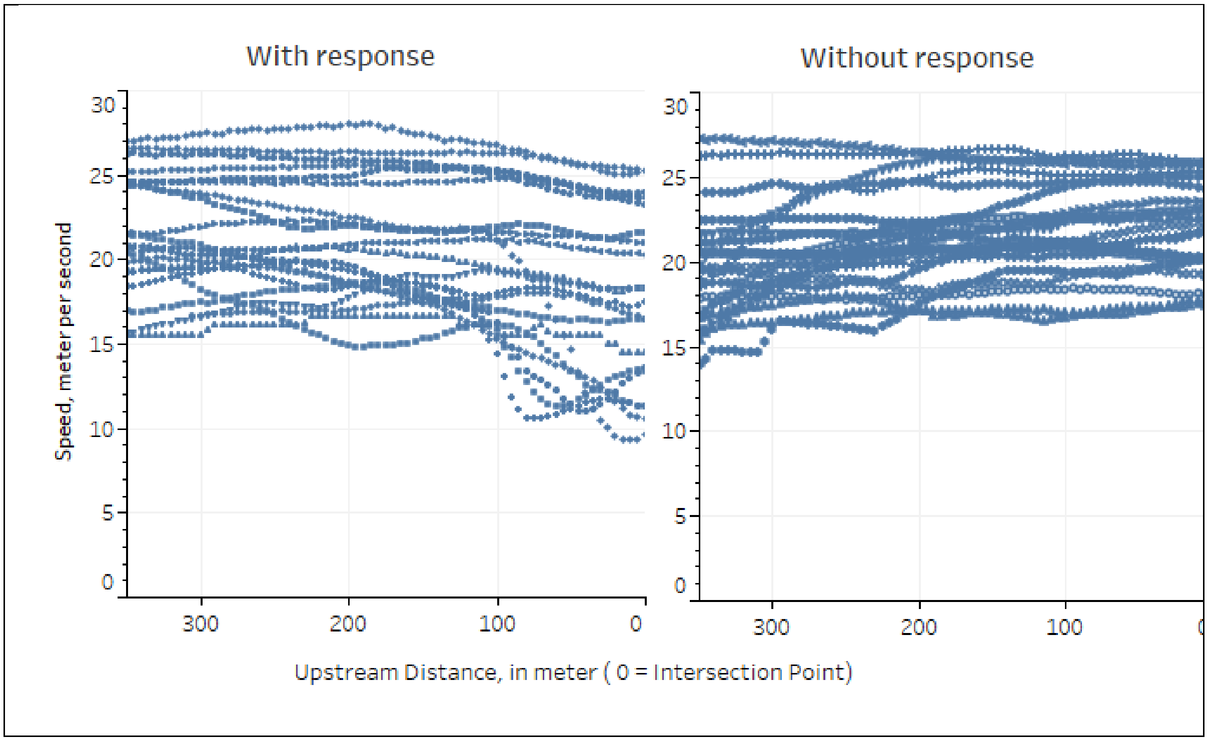

Figure 16 Plot of speed profile traces

Of the 223 time series traces, 71 showed a response point and the average reduction in speed was 5.0 mph (standard deviation (std) of 6.0). Figure 17 shows the distribution of detected response points. It includes the distribution of response points upstream of intersections with the average response point at 185.55 meters upstream of the upcoming intersection (std or standard deviation of 91.1). As noted, most drivers responded 100 meters upstream or earlier.

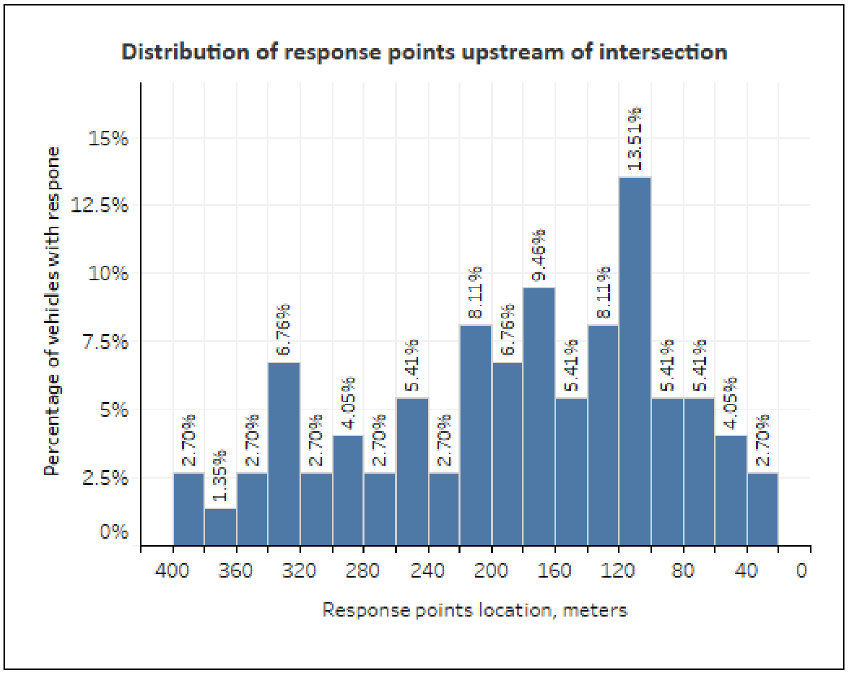

Figure 17 Distribution of detected response

Response points were identified for each time series traces using speed as a dependent variable as described previously. Next a mixed effect logistic regression model was used to assess corresponding characteristics associated with a response versus no response. The "Segmented" package in R was used to fit the linear regression model. Table 2 shows a summary of the data utilized in the model. The data included different intersection and driving characteristics. Both T and 4-way intersections with minor approaches controlled by stop signs were used. In Table 15, 191 and 32 traces were available during day and night conditions respectively. Only 15 traces were associated with the wet pavement. As noted, the only countermeasures included in the analysis were pavement markings and the Intersection Advance Warning Signs (IWS). IWS are static sign which warn the driver on the mainline of an upcoming intersection (i.e. W2-1 as noted in Figure 18.

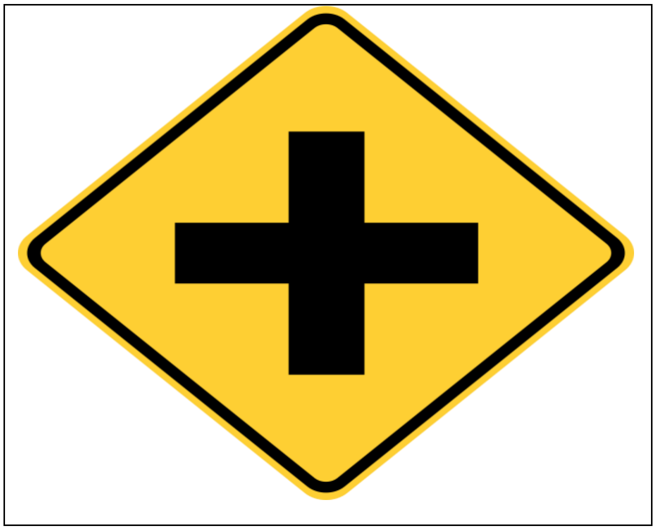

Figure 18 W2-1 sign (image source: commons.wikimedia.org/wiki/File:MUTCD_W2-1.svg)

Presence of vehicle at the minor street was noticed during the arrival of 21 traces. Out of 223 traces, only 86 traces were associated with the speed limit of below the posted speed limit at the reference point of 350 meter upstream and remaining were travelling above the limit at that point. 95 traces were associated with the speed limit of over 5 miles per hour at that point. Based on the location of intersection advance warning signs (IWS), posted speed limit, location of average response point and visibility of intersection from the major approaches, the study defined 350 meter as a suitable distance to compare driving speed with the posted speed limit of that approach. Speed different at the reference point was estimated from all 223 traces. Driver information were summarized in terms of experience, crash record, and gender. For instance, 217 traces were associated with drivers with zero crash experience. 85 traces were from female and remaining 138 were from the male drivers.

Table 15 Summary of driver and environmental characteristics

Variable		Count / Average (in decimal)	Minimum	Maximum	Std. Dev
Total traces		223			
Dependent variable (Response Point / Yes = 1)		71			
Unique Driver ID		27			
Unique Intersection ID		14			
	T-Intersection	9			
	Four way	5			
Time of a day					
Time of a day	Day and Night	191 and 32			
Weather					
Pavement Condition	Dry and Wet	208 and 15			
Traffic Scenario					
Vehicle at minor street (Yes = 1)		21			
Vehicle at opposite major street inside intersection at the time subject vehicle was within the study zone [With Vehicle @ Major Stream] (Yes = 1)		39			
Driving Characteristics					
Traces with travelling speed below posted speed limit at IWS (at 350 m)		86			
Speed difference at 350 meter upstream (Speed at 350 m – Posted Speed Limit)		2.514	-15.427	-18.682	8.716
Number of traces with speed over 5 mph to the posted speed limit		95			
Driver Information					
Years of driving		223	1	72	
Number of crashes	0	217			
	> 1	6			
Number of violations	0	99			
	> 1	124			
Gender	Female and Male	85 and 138			

Table 16 focuses on intersection characteristics. A total of 135 traces were associated with the T and remaining traces were associated with 4-way intersection. Only 5 traces at two different intersections were identified within a curve. IWS were identified at 6 intersections with 127 traces. Only one intersection was identified with separate left turn and pedestrian walking at the intersection with few traces.

Table 16 Summary of the intersection characteristics

Intersection Characteristics	Number of Traces	Number of Intersections
T Intersection = 1, 4- way = 0	135 and 88	9 and 5
Number of traces in Curve (Yes = 1, No = 0)	5	2
Posted Speed at major approach, mph	30 and 45	-
Presence of IWS at major approach (Yes = 1)	127	6
Separate turning lanes at major approach (Yes = 1)	4	2

To find different factors associated with response points upstream of intersections, a mixed effect logistic regression model was developed with response point as a binary variable. Driver and Intersection ID were used as a random factor to address their repetition effect. Independent variables used were drivers' and intersection characteristics, driving information like speed, weather factors upstream of intersection. Features with small sample size were not included in the model. A "glmer" function in lme4 package in R was used to develop the model. Models were compared using AIC and best fit model was finally used by the study. In addition, fitting of the model was also checked by visualizing residuals in R. Table 17 shows the final best fit model with associated variables.

Table 17 Model results

Fixed Effect	Estimate	Standard Error	p-value	Odds Ratio (OR)
Intercept	-1.504	0.885	0.089	0.222
Driver Information				
Sex (Male =1)	0.823	0.580	0.156	2.277
Years of Driving less than 5 years	1.475	0.630	0.019	4.371
Driver with number of violations	-0.006	0.532	0.991	0.994
Intersection Scenario				
With Vehicle @ Minor Stream	1.264	0.562	0.024	3.538
With Vehicle @ Major Stream	-0.870	0.507	0.086	0.419
Driving Characteristics				
Speeding above 5 mph	1.916	0.383	0.000	6.797
Features of Intersection				
Presence of IWS upstream	0.719	0.991	0.468	2.053
Day or Night Condition				
Time of a day (Day)	-0.706	0.476	0.138	0.494
Random Effect	**Groups**	**Variance**		
	Driver ID	0.001		
	Intersection ID	1.253		

Number of observations: 223, Groups: Diver ID = 27; Intersection ID = 14

The odds ratio shows the intensity of each significant variables on the existence of the response point. As noted male drivers were 2.277 more likely to show a response than female drivers. Drivers with less than 5 years of experience driving were 4.371 times more likely to show a response compared to more experienced drivers. Drivers were also 2.053 times more likely to show response to the upcoming intersection when minor stream vehicles were present. When a through a vehicle was oncoming in the opposite direction, drivers were one-third less likely to show a response. When a driver was traveling 5 or more mph over the posted speed limit, they were 6.797 more likely to show response point compared to drivers who were traveling within 5 mph or the speed limit or less.

4.4 Conclusion and Discussion

The main objective of this study was to analyze driving behavior of through moving vehicles upstream of intersections by detecting response points in the speed profile. Out of 223 traces, about 32% of drivers showed response to the intersections by decreasing speed by at least 3 miles per hour.

A model was developed to find different factors associated with the response point upstream of intersections. Male drivers were likely to show response to intersection compared to female drivers. Non experienced drivers were found to be aware of the intersection ahead compared to experienced drivers. The reason might be associated with confidence of drivers, driving ability etc. The study initially assumed the number of violations associated with drivers as a strong variable to response point but it was not found significant in the model.

Vehicles were more likely to show response to intersection at the time of presence of vehicles at the minor approaches. However, the presence of major approach through moving vehicles approaching in the opposite direction at the time when subject vehicle was within the study zone was found to have reverse effect. It shows through moving vehicles at the major approaches are more skeptical of vehicles at minor approaches and might be due to their possible turning maneuver but are more confident when drivers noticed vehicles traversing the intersection from the opposite direction.

Drivers only operating above the speed of 5 miles per hour than posted speed limit were more likely to show response point. It shows that drivers were more alert at the time of speeding when crossing the intersection. It shows the need of posted speed limit signs upstream of intersections to control vehicles speed. Intersections with intersection ahead warning signs was found to affect the response point positively. It shows the importance of sign in warning the drivers approaching the intersections. Though the sample size was limited, drivers were more likely to response point when traversing through the intersections within the curve. It might be the dual effect of geometry of major approach and intersection. As not expected, drivers traversing the intersections both night and day time drivers were showing similar driving behavior. Other variables like education, age of drivers, driver characteristics like fun taking risk, crash history were not found to be significantly effective.

Overall, the result showed that drivers were more likely to be aware of the traffic scenario at intersection ahead. Speeding drivers were found to be more aware of intersection. In addition, the result support the installation of intersection ahead warning signs upstream of intersections.

4.5 Study Limitations

Significant number of traces were removed from the analysis due to the subject vehicle following too closely to the vehicle ahead as only free flow vehicles were considered for the analysis. In addition, some intersections were only associated with the limited traces. The study also could not cover different types of treatments applied at major approach due their unavailability in the available data set. Some of the speed traces were available with excessive noise and were removed from the analysis. Due to this reason the study did not focus on the effectiveness of the countermeasure, rather consider other driving factors to evaluate their effect.

4.6 Acknowledgements

The team would like to thank the Federal Highway Administration (FHWA) and the Iowa Department of Transportation for funding this research, the Virginia Tech Transportation Institute for their assistance in obtaining the SHRP2 data, and the Center for Transportation Research and Education (CTRE) at Iowa State University for providing the RID data.

4.7 References

Abou-Henaidy, M., S. Teply, and J. D. Hunt. Gap Acceptance Investigations in Canada. Proceedings of the Second International Symposium on Highway Capacity, 1994, Akcelik, R. (ed.), Volume 1, pp. 1-20.

Bared, J., W. Hughes, R. Jagannathan, and F. Gross. "Two Low Cost Safety Concepts for Two Way Stop Controlled, Rural Intersections on High Speed Two Lane, Two Way Roadways." Report No. FHWA-HRT-08-063, Federal Highway Administration, Washington, DC. (2008).

Caird, J.K., C.J. Edwards, J.I. Creaser, and W.J. Horrey. Older driver failures of attention at intersections: using change blindness methods to assess turn decision accuracy. Human Factors. Vol. 47 (2). 2005. pp. 235–249.

Campbell, B.N., J.D. Smith, and W.G. Najim. Analysis of Fatal Crashes Due to Signal and Stop Sign Violations. National Highway Traffic Safety Administration, US Department of Transportation. DOT HS 809 779. Sept. 2004.

Chovan, J.D., L. Tijerian, J. H. Everson, J. A. Pierowicz, and D. L. Hendricks. Examination of intersection left turn across path crashes and IVHS countermeasures (DOT HS 808 154). National Highway Traffic Safety Administration. 1994.

Davis, G.A., and T. Swenson. Field study of gap acceptance by left-turning drivers. Transp. Res. Rec. 1899, 2004, 71–75.

Godavarthy, R.P., E.R. Russell, and B. Mirzazadeh. Speed Reduction Mitigation Strategies on Rural Highways at Two-Way Stop Control Intersections and Curves. Journal of Transportation Technologies, 7, 2017, 423-437. https://doi.org/10.4236/jtts.2017.74027.

Gonzalez, R. P., G. R. Cummings, H. A. Phelan, M. S. Mulekar, and C. B. Rodning. Does Increased Emergency Medical Services Prehospital Time Affect Patient Mortality in Rural Motor Vehicle Crashes? A Statewide Analysis. The American Journal of Surgery, Vol. 197, pp. 30-34. 2009.

Guerriera, J.H., P. Manivannanb, and S.N. Nair. The role of working memory, field dependence, visual search, and reaction time in the left turn performance of older female drivers. Applied Ergonomics. Vol. 30 (2). 1999. pp. 109–119.

Harder, K. A., J. Bloomfield, and B. J. Chihak. Reducing Crashes at Controlled Rural Intersections. July 2003, Minnesota Department of Transportation, Report no. Mn/DOT 2003-15.

IIHS. Roadway and Environment. Insurance Institute for Highway Safety, Highway Loss Data Institute.http://www.iihs.org/iihs/topics/t/roadway-and-environment/fatalityfacts/roadway-and-environment. November 2016

Keay, L., S. Jasti, B. Munoz, K.A. Turano, C.A. Munro, D.D. Duncan, K. Baldwin, D. J. Baneen-Roche, E.W. Gower, and S.K. West. Urban and rural differences in Older drivers Failure to Stop at Stop Signs. Accident Analysis and Prevention. Vol. 41, Issue 5. September 2009. pp. 995-1000.

Manual on Uniform Traffic Control Devices (MUTCD). (https://mutcd.fhwa.dot.gov/).

McGwin, G. and D.B. Brown. Characteristics of Traffic Crashes among Young, Middle-aged, and older Drivers. Accident Analysis and Prevention. Vol. 31, Issue 3. May 1999. pp. 181-198.

Montella, A., M. Aria, A. D’Ambrosio, F. Galante, F. Mauriello, and M. Pernetti. Simulator evaluation of drivers’ speed, deceleration and lateral position at rural intersections in relation to different perceptual cues. Accident Analysis and Prevention, Vol. 43, Issue 6, 2011, pp. 2072-2084.

Muggeo, V.M.R. R Package to Fit Regression Models with Broken-Line Relationships. R News, Vol. 8, No. 1, 2008, pp. 20–25.

Preston H, R. Storm, M. Donath, and C. Shankwitz. Review of Minnesota's Rural Intersection Crashes: Methodology for Identifying Intersections for Intersection Decision Support. Minnesota Department of Transportation. St. Paul, MN. MN/RC-2004-31. 2004.

Spek, A.C.E., P. A. Wieringa, and W. H. Janssen. Intersection approach speed and accident probability. Transp. Res. Part F: Traffic Psychol. Behav. 9, 2006, 155–171.

Yan, X., E. Radwan, and D. Guo. Effects of major-road vehicle speed and driver age and gender on left-turn gap acceptance. Accident Analysis and Prevention 39 (2007) 843–852.

CHAPTER 5. CONCLUSION AND DISCUSSION

5.1 General Conclusion

The study used the common driving behavior analysis approach at work zones and rural intersections to increase the safety at those zones with detail insight on driving behavior using various features like roadway, driving (kinematics like speed), and driver information.

The result from Chapter 2 showed that first work zone sign was not significantly affecting the driving behavior. Only speed limit, lane ends and CMS were found to be affecting the driving behavior. Active CMS was found to be more effective compared to not active CMS sign. Effect of overlapping signs was not found to have significant effect on the driving behavior. Except at speed limit signs, drivers were more likely to show response to the signs placed near to the work zones. Speed limit with both work zone and feedback type were found to be significantly effective compared to normal speed limit signs with no indication of work zone. Speeding drivers were more likely to show response at different work zone signs with exception for drivers speeding at first sign. Distracted drivers were less likely to show response at work zone signs. In addition, driver information and other environmental factors were not found to be significant in the model.

The analysis of the driving behavior of both right and left turning vehicles from major approach to the minor approach of rural two way stop controlled intersections in Chapter 3 showed that right turning vehicles showed early reaction point around 20 meters ahead compared to left turning vehicles. It might be due to the reason some left turning driver's needs to completely stop searching for safe gap between upcoming vehicles approaching intersections from the opposite direction. The distribution of reaction points also showed that more than 70% of drivers showed reaction within 300 meters upstream of intersection for both types of turning maneuver. However, there are few reaction points associated with larger distances and were mostly associated with bad weather scenario like snowy road, raining and driving during night time. In addition, driving speed at reaction point was found to positively affect the location of reaction point. The result also showed that presence of intersection ahead warning signs helped drivers to reduce reaction point while on pavement marking was found to have just an opposite effect. It shows drivers reacted quicker at on-pavement marking showing the intersection ahead sign. It might be due to drivers more familiarity with posted signs compared to on-pavement marking showing the same information. However, the effect of flashing beacons that flashes yellow light for major approach vehicles and red light for minor approach vehicles, multilane approach compared to single lane, and lanes with no pavement lining were not found to affect the reaction location. Drivers were also found to show reaction near to the intersection in day time compared to night time and might be due to the visibility. Similarly, drivers were more likely to show reaction point far away from intersection when the road was wet due to snow or rainy day compared to dry pavement.

Driving behavior analysis of through moving vehicles from the major approach of rural two way stop controlled intersections showed that male drivers were likely to show response to intersection compared to female drivers. Non experienced drivers were found to be aware of the intersection ahead compared to experienced drivers. When there was a vehicle at the minor approaches on the arrival of subject vehicles (i.e. major approach through moving), vehicles were more likely to show response to intersection However, the presence of major approach through moving vehicles approaching in the opposite direction at the time when subject vehicle was within the study zone was found to have reverse effect.

Drivers operating above the speed of 5 miles per hour than posted speed limit were more likely to show response point. It shows that drivers were more alert at the time of speeding when crossing the intersection. Intersections with intersection ahead warning signs was found to affect the response point positively As not expected, drivers traversing the intersections both night and day time drivers were found to show same response. Other variables like education, age of drivers, driver characteristics like fun taking risk, crash history were not found to be significantly effective.

5.2 Future Work

In work zone study, inclusion of variables like police patrol car, weather conditions in low visibility (especially snow and fog) in the model is suggested. A separate study on the effect of various distracting sources in both advance warning area and inside the work zone might show the intensity of distracting potential of various sources at different locations. A connected vehicle environment where drivers get alert on the presence of work zone signs, locations might be of great interest to analyze driver's compliance to different work zone signs.

At rural intersections, it is suggested to collected traces at intersections with various countermeasures. Though there are only limited countermeasures applied at the major approach of the rural stop controlled intersections, countermeasures like painting on the roadway, flashing beacon can be included in the model. Driving behavior of both major and minor approach vehicles in a connected vehicles environment (connection between minor and major approach vehicles) at rural intersections would be an interesting topic to conduct research on.

APPENDIX A. SPEED TRACES USED FOR WORK ZONE STUDY

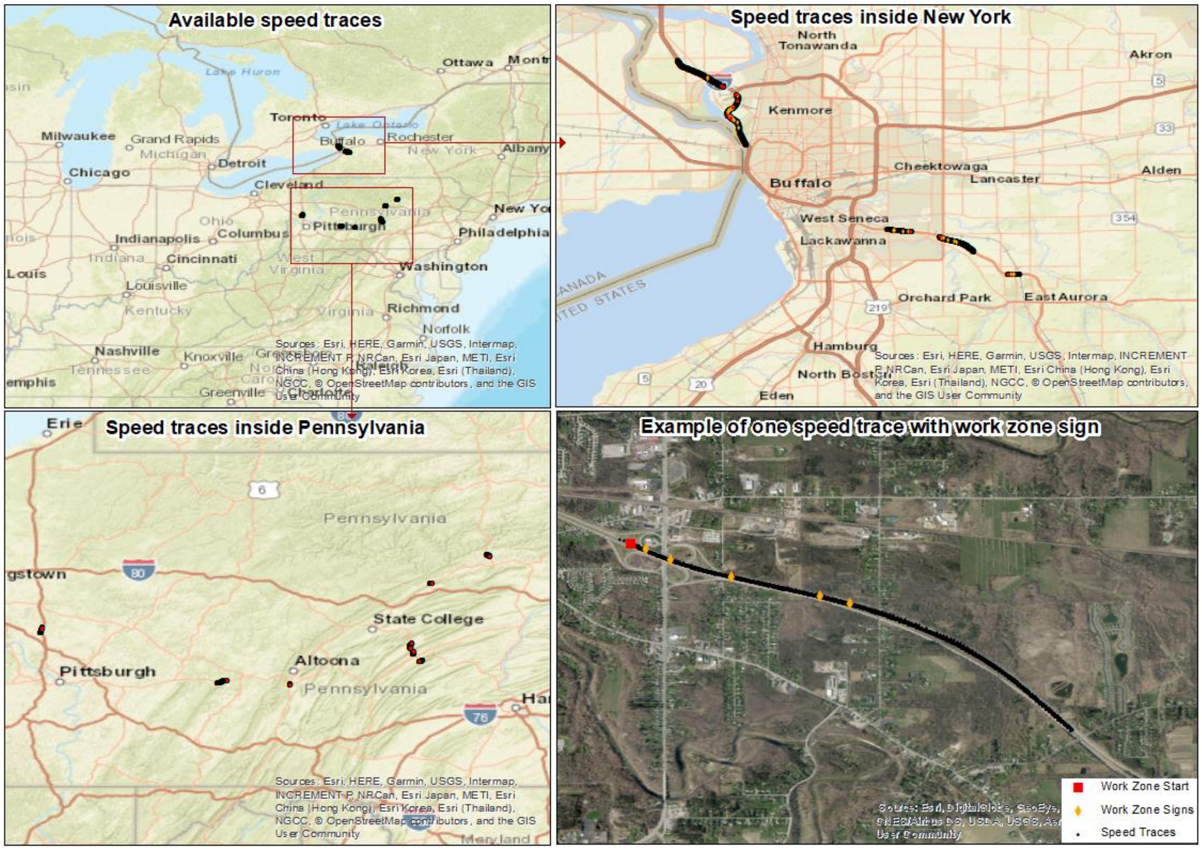

Figure A.19 Speed traces used for the work zone study

APPENDIX B. WORK ZONE ANALYSIS AREA

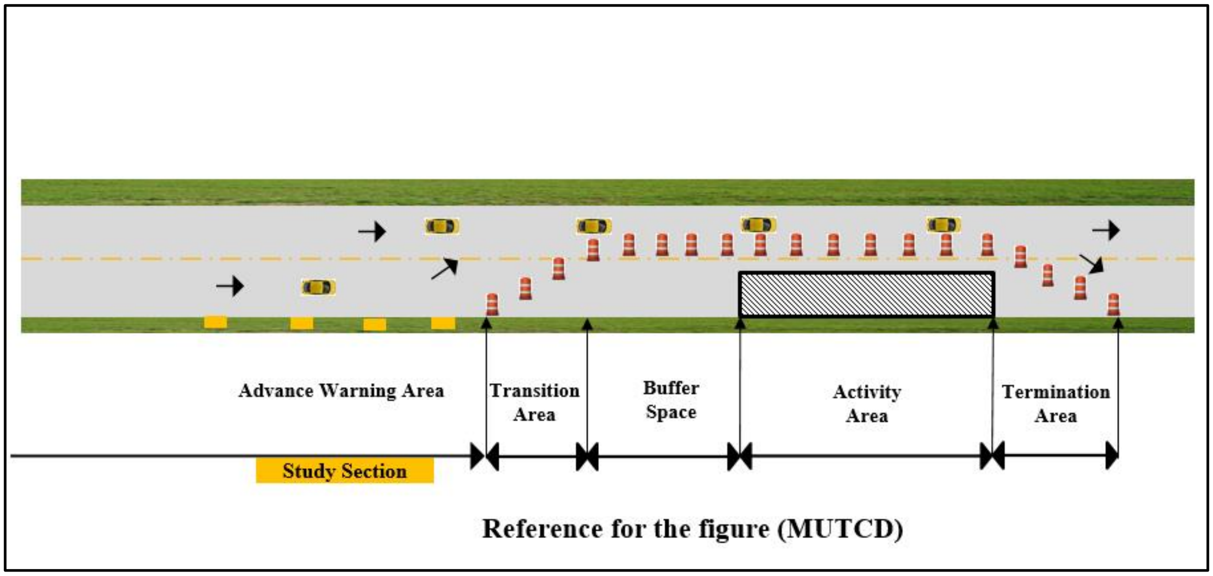

Figure B.20 Study section for work zone

APPENDIX C. DETECTED REACTION POINT AT WORK ZONE

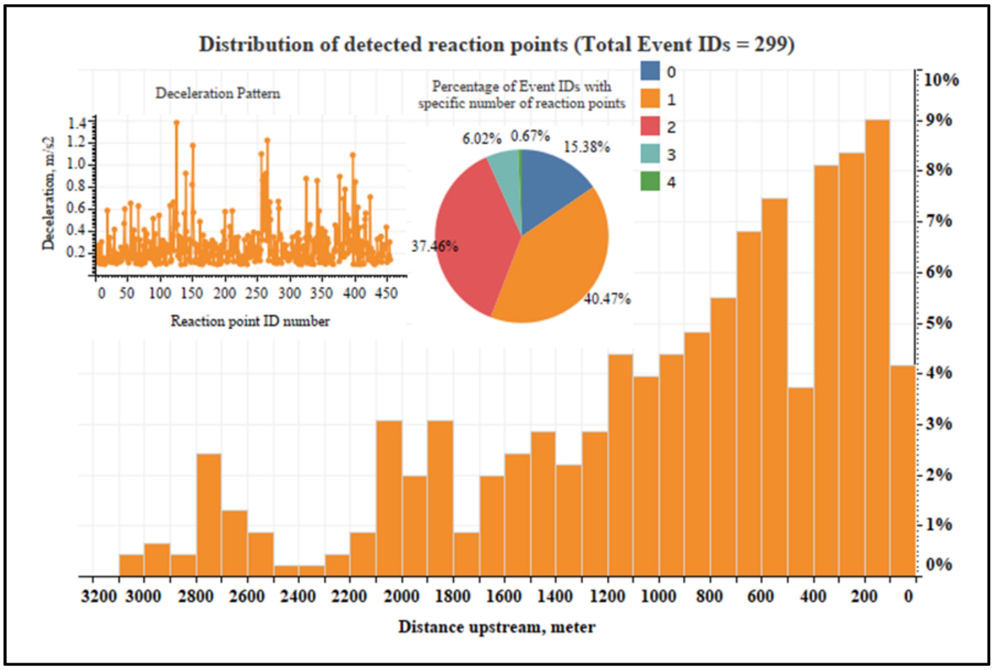

Figure C.21 Distribution of detected reaction points from all 299 traces

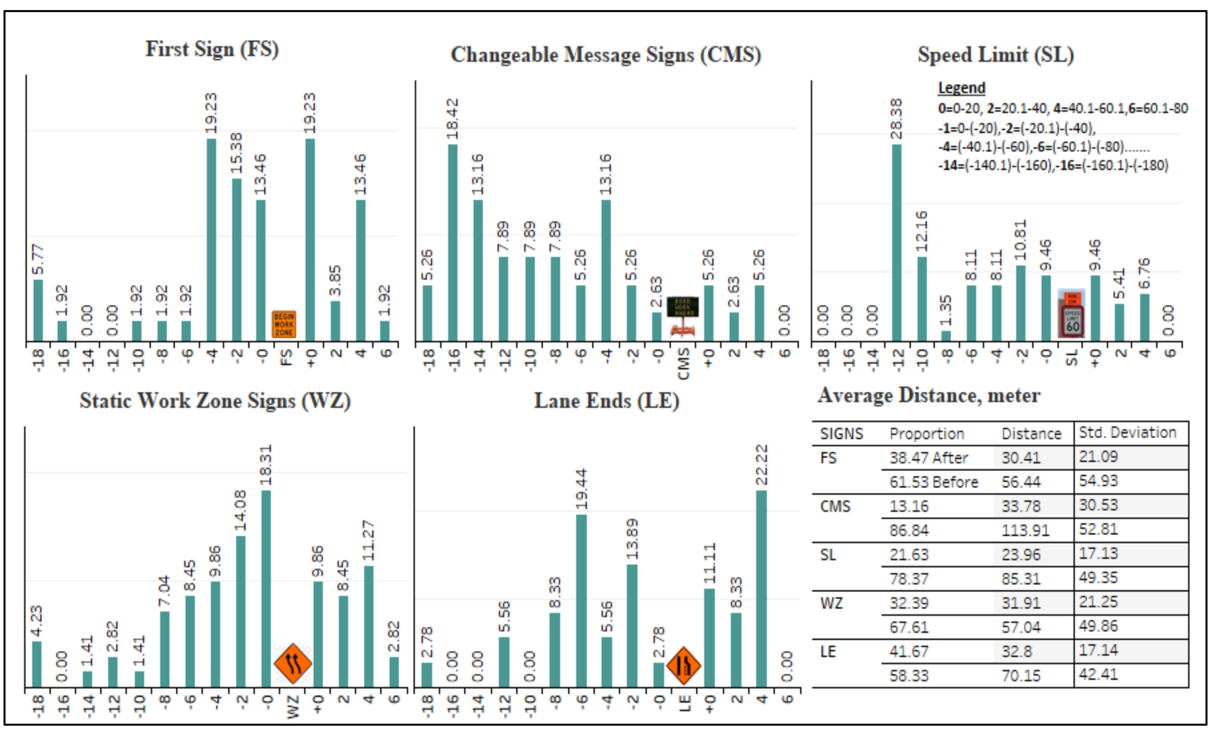

Figure C.22 Location of the response points at different work zone signs

Table C 18 Location of response points at different speed threshold (≥ 3mph / ≥ 4 mph / ≥ 5 mph)

Signs	Location	Proportion of response points, %	Average Distance of response point, in meter	Standard Deviation
First Sign	Before	61.53 / 55.63 / 53.82	56.44 / 55.63 / 53.82	54.93 / 45.93 / 46.88
	After	38.47 / 42.10 / 51.61	30.41 / 34.44 / 37.50	21.09 / 21.56 / 22.09
CMS	Before	86.84 / 83.87 / 82.61	113.9 / 114.64 / 120.04	52.81 / 50.57 / 50.13
	After	13.16 / 16.12 / 17.39	33.78 / 23.53 / 28.75	30.53 / 19.43 / 17.94
Speed Limit	Before	78.37 / 78.69 / 79.24	85.31 / 85.71 / 85.32	49.35 / 45.27 / 45.73
	After	21.63 / 21.31 / 20.75	23.96 / 21.26 / 22.35	17.13 / 16.49 / 17.71
Static Work Zone	Before	67.61 / 63.33 / 60.78	57.04 / 56.22 / 57.86	49.86 / 49.78 / 51.44
	After	32.39 / 36.67 / 39.21	31.91 / 31.10 / 32.37	21.25 / 21.39 / 22.04
Lane Ends	Before	58.33 / 53.12 / 55.17	70.15 / 75.09 / 78.04	42.41 / 44.49 / 44.09
	After	41.67 / 46.87 / 44.83	32.80 / 32.81 / 30.54	17.14 / 18.53 / 18.93

APPENDIX D. DATA REDUCTION DICTIONARY

Roadway characteristics such as number of lanes, regular speed limit, and roadway geometry were queried from the RID. Work zone characteristics such as direction of travel, lane or shoulder closures, types and location of work zone signs, vehicle lane position, start of work zone, and presence of vehicle ahead (if any) were manually extracted from the forward video. Time of day and roadway surface condition (wet versus dry) were also reduced from the forward video.

Work zone characteristics were reduced from the beginning of the advance warning area to a few meters downstream of the transition area. A data reduction template and data dictionary was prepared at the beginning to maintain consistency among many data reducers. Different roadway characteristics and work zone signs information were reduced looking at the front video available from SHRP 2 data.

Driver information were already provided through the naturalistic driving data sources including the age of driver, driving experience, crash record, and gender. Distraction were reduced separately at the VTTI research center. The following list contains few important roadway and work zone signs information manually reduced from the forward video.

Rodway configuration prior to work zone: It was reduced as either 2 lane undivided or divided, 4 lane divided or undivided divided, or Multilane. Changes in the roadway features were reduced accordingly.

Median type prior to the work zone: In addition to the roadway features, the median type was reduced to check how the movement of vehicles were separated. The most frequently reduced median type were Concrete median barrier, Depressed median barrier, Depressed median without barrier, Flushed median with barrier, Flushed painted median without barrier Raised median without barrier, Guardrail, Road diet, and painted only median as a center line. Snapshot of each type of median were provided to the data reducers before start of the task to make uniformity in the data reduction.

Type of barrier: In case of the presence of barrier at the median like Cable median, Guardrail or Concrete, they were reduced accordingly.

Work Zone Configuration: It was reduced if the work zone ahead was only shoulder or lane or both shoulder and lane closure. The number of lanes closed were reduced in case of lane closure scenario. Some of the common features of work zone configurations were head to head traffic with or without shoulder closed, left or right lane closed, left or right shoulder closed or alternate left and right shoulder or lane closed.

Presence of glare screen: The section where glare screen was installed especially at the median were reduced. Figure D.23 below shows an example of glare screen used at work zones.

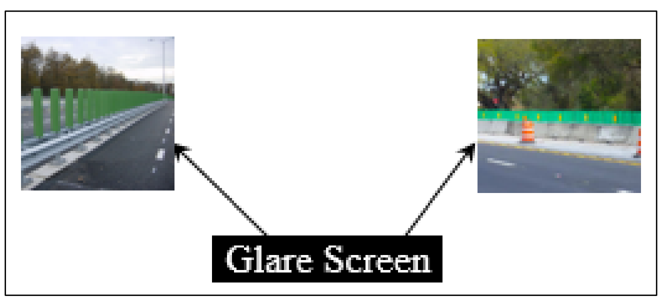

Figure D.23 Glare screens used at median of work zones

Channelizing device: It was reduced to specify the device that channelizes the traffic inside work zones. The frequently reduced channelizing devices were concrete or Jersey barrier, cones, barrels or pylons or vertical panels or combination of different devices. The location of the device was also reduced accordingly.

Work Zone Signs: It included all normal work zone warning signs such as “Road Work Ahead” or “Begin Work Zone”, “End of Work Zone”. Work zone signs in the advance warning area were reduced as Type 1 and signs within the work zone starting from the first taper till the end of work zone were reduced as Type 2 in order to differentiate signs in different sections of work zones. Attempt was made to reduce the letter inside the work zone signs too but due to the location of signs, time of a day (night time), weather (rainy) conditions and quality of the front video it was not always feasible to reduce the letters. In addition to the signs with letters inside, warning signs showing the change in the roadway alignment ahead like ramp merging from the right, lane shift, and narrow lane were also categorized under work zone signs. Overall, most of the work zone signs reduced were typically warning and guide signs to the upcoming change. Figure D.24 below shows the snapshot of some of the reduced work zone signs.

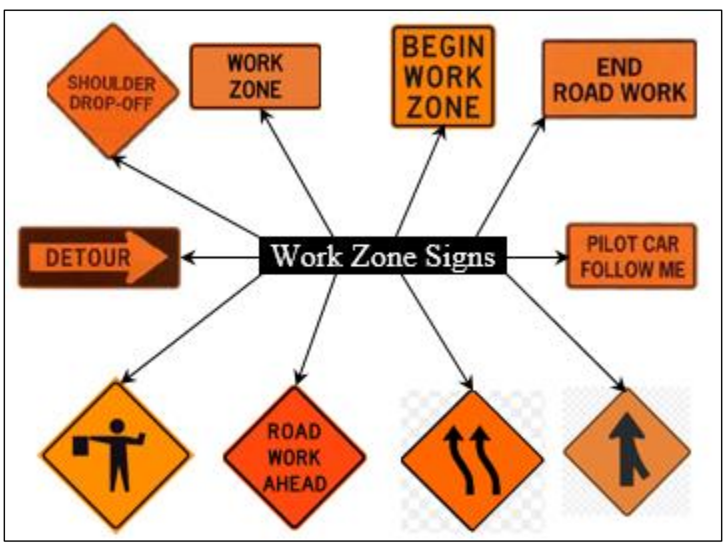

Figure D.24 Normal work zone signs reduced (Source: Google Image 2018)

Variable Message Signs (VMS or CMS): It refers to the digital message signs placed on the side or overhead of the road showing information relevant to work zone ahead as shown in Figure D.25 . It was further reduced as either “trailer” mounted on the side of the road or “over” mounted on the top of the road. Depending on if it was flashing information or not, it was reduced either active or not active. Similar to the normal work zone signs, attempt was made to reduce letters displayed. But the letters were not always legible in the video due to time of a day, weather and quality of the video itself. In addition, the sign with digital arrow which inform drivers to merge on the moving lane was also reduced as VMS but tagged separately as arrow sign.

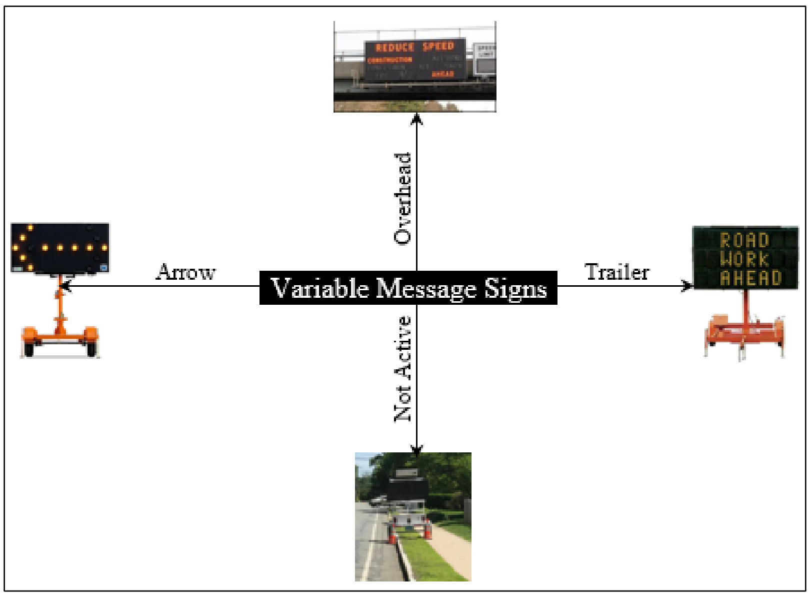

Figure D.25 Variable message signs or Changeable message signs (Source: Google Image 2018)

Speed Limit: It refers to the regular posted speed limit signs, work zone specific speed limit signs (WZ), or speed feedback signs. Normal speed limit signs were existing regulatory speed limit signs. For the upstream section, they served as the regulatory speed limit unless a work zone speed limit superceded the normal speed limit. Work zone speed limit signs were reduced as work zone type when they were placed additionally specific to work zone and usually provided in orange color background. The remaining type, feedback, displayed flashing numbers of individual vehicle speed usually with posted speed limit on the top. Figure D.26 below shows the detail of different types of speed limit signs reduced. In addition, speed limit signs were also reduced as Trailer or Post mounted based on the placement of the signs.

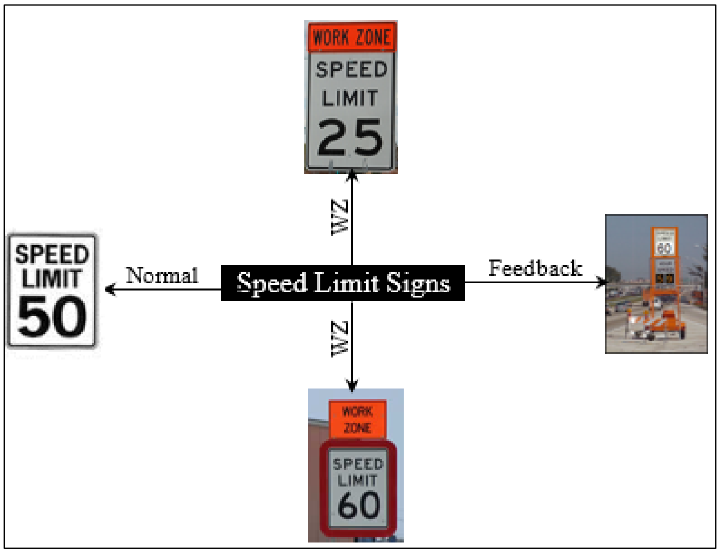

Figure D.26 Different types of speed limit signs (Source: Google Image 2018)

Enforcement Signs: It includes signs that provided information on penalties for driver actions in work zones such as “Work Zone: Traffic Fines Double”. Only enforcement signs relevant with the work zone were reduced in this study. Figure D.27 below shows the snapshot of few enforcement signs reduced.

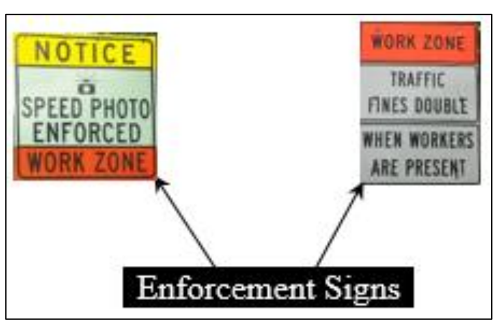

Figure D.27 Example of enforcement signs (Source: Google Image 2018)

Lane Ends: It indicates a lane merge was ahead for work zones where a lane was closed. The signs was only available at work zones with lane closure. Figure D.28 below shows the types of lane ends signs used at work zones.

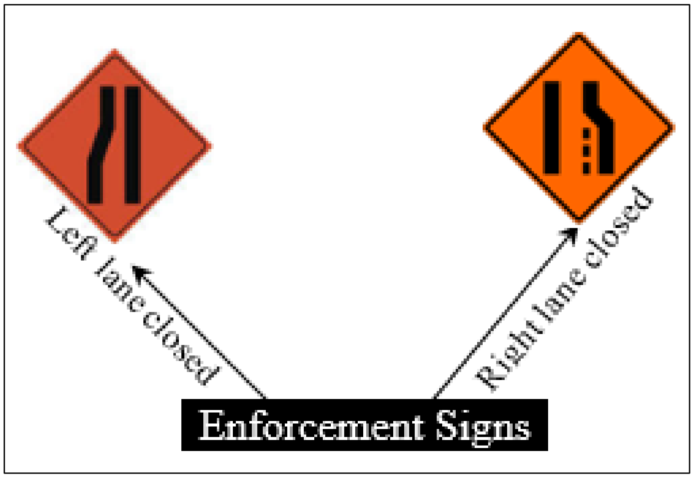

Figure D.28 Lane ends signs (Source: Google Image 2018)

First Sign: It was the first work zone related sign that a driver was presented with as they entered the work zone advance warning area. It is the first sign that indicates work zone ahead. Any type of work zone sign can be the first sign. In this study, normal work zone signs and VMS or any of the signs discussed above were used as First Sign and was reduced accordingly.

Overlapping Effect: The study assigned legibility distance for each types of sign discussed above. In short, the legibility distance was defined as the distance from which the sign was legible (not visible). Due to multiple signs placed close to each other, there were numerous scenario where, multiple signs were legible from a certain section. In addition, it was difficult for the study to assign effect due a particular signs. Thus, when multiple signs were legible from a section, it was considered due to effect of multiple signs and was termed as overlapping effect. The overlapping was more dominant near to the start of work zone where multiple signs were placed close to each other.

In addition to location and type of signs, presence of vehicles ahead, lane merge locations, presence and location of equipment and workers, time of a day, and weather information were also reduced.

Lane merge location were reduced starting from the instance vehicle start merging to the instant vehicle changed the lane until the vehicle aligned to the merged lane.

Location of vehicle was reduced as if it was moving on right, center, left, center right or center left lane.

Presence of vehicle ahead was reduced to check if the subject vehicle was moving in the free flow in addition to its visibility to different signs. It was only reduced if the vehicle ahead was affecting the movement of subject vehicle or within 3 seconds gap size.

Location of equipment and workers were reduced in terms of their location (inside work zone or near to the moving lane), device separating it with the moving lane and distance of equipment or workers from the moving lane to tentatively estimate the exposure for safety analysis.

Time of a day was reduced as if it is night or day. Dawn and dusk was not categorized separately due to the limited sample size with in that category.

Weather was reduced if it was dry or rainy day.

Figure D.29 below shows the snapshot of the data reduction template used by all the data reducers as a reference. In case of any new information encountered during the data reduction procedure, the team discussed to come up with the final decision. The purpose of it was to maintain consistency among the data reducers. With uniformity in the reduced information significantly reduced the time of processing the data at the time of analysis.

	Upstream of Work Zone (WZ)		Information
4	**First Sign**		Code timestamp
5	**Work Zone Sign**		Code timestamp
	Type: *1 or 2*		Code type of work zone sign
6	Work Zone Sign		Code timestamp
	Type: *1 or 2*		Code type of work zone sign
7	**Variable Message Sign (Active or Not)**		Code timestamp
	Status		Code if it's active or not
	Active: See Data Dictionary for detail	The sequence of signs 5 to 11	
	Not Active	might be different for different	
8	**Speed Limit**	work zones or even traces with	Code timestamp
	Type of speed limit	in the same work zone.	Code type of speed limit sign
	Normal		
	Work Zone Speed Limit		
	Feedback speed limit		
9	**Work Zone Sign**		Code timestamp
	Type: *1 or 2*		Code type of work zone sign
10	**Work Zone Sign**		Code timestamp
	Type: *1 or 2*		Code type of work zone sign
11	**Lane Merge Sign**		Code timestamp
12	**Road Configuration prior to work zone**		Code type of road configuratio
	4 lane divided		
	2 lane divided		
	4 lane undivided		
	2 lane undivided		
	multilane divided		
	NA		
13	**Median type prior to work zone**		Code type of median
	Concrete Barrier median		
	Depressed median with Barrier		
	Depressed median without barrier		
	Flushed median with Barrier		
	Flushed Painted Median without barrier		
	Raised median without barrier		
	Rasied median with Barrier		
	Guardrail		
	Road diet		
	Painted Only as a center line		

	Work Zone Area	
14	**Start of work zone**	Code timestamp
15	**Work Zone Confifuration**	Code work zone configuration
	head to head traffic with shoulders closed	
	head to head traffic without shoulder closed	
	left lane closed	
	right lane closed	
	left lane and left shoulder closed	
	right lane and right shoulder closed	
	right shoulder closure	
	left shoulder closure	
	Alternate right and left shoulder	
16	**Channelizing device**	Code type of chanellizing devic
	concrete/jersey barrier	
	cones	
	barrels	
	NA	
	Cones and Concrete barrier	
17	**Location of Channelizing (edge or median or both)**	Code location of chanellizing dev
	Edge	
	Median	
	Both	
	NA	
18	**Lane Shift (Yes or No)**	Code if there is lane shift
19	**Presence of worker (Yes or No)** *(Code if it's YES)*	
	If yes:	
	Location of worker : It mean code time stamp	Code timestamp
	Type of exposure	Code type of exposure
	Near to the moving lanes	
	Inside work zone: Inside work zone and far away from moving lane	
20	**Presence of equipment (Yes or No)** *(Code if it's YES)*	
	If yes:	
	Location of equipment: It mean code time stamp	Code timestamp, if present
	Type of exposure	Code type of exposure
	Near to the moving lanes	
	Inside work zone: Inside work zone separated by channelizing device	
	Type of equipment	Code type of equipment
	Construction Truck (Tippers, Dumbers,Trailers,Tankers)	
	Earth Moving Equipments (Excavators, Graders, Loaders, Backhoe, Bulldozer...)	
	Material Handling Equipment (Crane or Conveyors): Are usually stationary	
	Police Car	
	Note: If multiple equipments are present in series, code start and end of the series.	
21	**End of work zone (loaction of last taper)**	Code end of work zone
22	**End work zone sign**	Code ebd of work zone sign

Figure D.29 Data reduction template used as a reference

APPENDIX E. SAMPLE R SCRIPT FOR DISTANCE CALCULATION IN EACH SPEED TRACE

```
library("longitudinalData")
library("clv")
library("cluster")
library("class")
library("rgl")
library("misc3d")
library("plyr")

files <- list.files(pattern = "^.*csv")
length(files)

for (i in files){
   f <- read.csv(i)
   names(f)
   ID <- seq.int(nrow(f))
   newdata <- data.frame(f,ID)
   speed <- newdata$vtti.speed_network
   #speed[is.na(speed)] <- 0
   speed[1] <- 0
   speed[length(speed)] <- 0
   speednew <- approx(newdata$ID,speed,newdata$ID,method = "linear")
   speedmps_new <- speednew$y * 0.277778

   finaldata <- data.frame(newdata,speedmps_new)
   finaldata$Work.Zone.Sign.1

   #required_1 <- subset(finaldata, finaldata$vtti.timestamp <= ES & finaldata$vtti.timestamp >= f$vtti.timestamp[1])
   ff <- finaldata$speedmps_new/10
   #INT<- pmatch("Start",f$Work.Zone.Sign.1)
   INT <- which(grepl(pattern = "Start",finaldata$Work.Zone.Sign.1))
         ff[INT] <- 0
   install.packages("longitudinalData")
      ff[is.na(ff)] <- 0 # NA to zero
      #ff[length(ff)] = 0 # last item to zero
      fff_I <- rev(cumsum(rev(ff[1:INT]))) # from intersection point to start of time series
      fff_I[is.na(ff)] <- 0
      fff_I <- -(fff_I)

      ff_n <- finaldata$speedmps_new/10
      INT_n <- (INT-1)
      ff_n[INT_n] <- 0
      ff_new <- ff_n[INT_n:1]
      fff_II <- cumsum((ff_n[INT_n:length(ff_n)])) # from intersection point to downward
      fff_II[is.na(ff_n)] <- 0

      a <- data.frame(fff_I[1:INT])
      names(a)[1]<-paste("Distance_New")
      b <- data.frame(fff_II[2:(length(ff)-INT+1)])
      names(b)[1]<-paste("Distance_New")
      distance <- (rbind(a,b))
      required_2 <- data.frame(finaldata,distance)
      required_2[is.na(required_2)] <- ""
      head(required_2)

      F <- which(names(required_2) == "speedmps_new")
      G <- which(names(required_2) == "Distance_New")
      required_3 <- subset(required_2, select = c(1:83,F,G,84:(ncol(required_2))))

      write.table (required_3, paste0("Raju",i), sep =",", row.names= FALSE,append = FALSE)
}
```

APPENDIX F. SAMPLE R SCRIPT TO EXTRACT REDUCED WORK ZONE SIGNS INFORMATION, MERGE TRACES FOR ARCGIS, AND PLOTTING ALL SPEED TRACES AT ONCE

```
#Extract work zone sign information
  files <- list.files(pattern = "^*P1_.*csv")
  length(files)

  for (i in files){
  f <- read.csv(i)
  extracted <- data.frame(subset(f,(grepl("[A-z]",f$Work.Zone.Sign.1))))
  #v <- which(grepl("[a-z]",f$Work.Zone.Sign))
  extracted[is.na(extracted)] <- ""

  F <- which(names(extracted) == "Work.Zone.Sign.1")
  G <- which(names(extracted) == "Type")
  #G <- which(names(extracted) == "WithLegibility")

  d <- extracted[,c(F,G)] #
  data <- data.frame(i,d)
  write.table(data, "Coded Trace Information.csv", sep =",", row.names= FALSE, append = TRUE)
  }
```

```
##Sample r script used to merge coordinates in order to use for projection

  for (i in files){
   f <- read.csv(i)
   Time_Stamp <- f$vtti.timestamp
   FileID <- f$vtti.file_id
   Lat <- f$vtti.latitude
   Long <- f$vtti.longitude
   WithNA <- data.frame(i,Time_Stamp,FileID,Lat,Long)
   WithoutNA <- na.omit(WithNA)
   #WithNA[is.na(WithNA)] <- "" # This can be an alternate option
   write.table(WithoutNA, file="Merged Data.csv", sep =",",col.names=FALSE,append=TRUE)
  }
```

```
###Sample r script to plot speed profile of all the traces at once
  setwd("Z:\\Project\\SHRP 2 IAP P2 Work Zone\\Phase 2 Data\\Congestion\\NearCrash\\GoodTraces")
  files <- list.files(pattern = "^Event_ID.*csv")
  length(files)
  head(name)

  for (i in files){
   WZ <- read.csv(i)
   S <- WZ$speedmps_new
   D <- WZ$vtti.timestamp
   jpeg(paste0("C:\\Users\\rthapa\\Desktop\\CP_CrashNearCrash\\_",i,".jpeg"),width=7.5,height=7.5,units="in",res=500)
   plot(D,S, type="l", col="blue", axes = TRUE, lwd=2)
   dev.off()
}
```